Analyses of Koitash Landslide, Affecting Mailuu Suu Valley, Kyrgyzstan, Through Integrated Remote Sensing Techniques

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Abstract

This work presents an integrated application of remote sensing techniques on monitoring post event conditions of the Koitash landslide, affecting Mailuu Suu valley, Kyrgyzstan. This area is highly prone to landslide affecting the slopes next to the numerous radioactive waste rock dumps and tailings storage facilities disseminated along the valley. In this hazardous context, we propose a methodology to map the location of recent landslides, active slopes and strong surface variation, over large areas. The analysis is tested on the Koitash landslides and combines several remote sensing datasets. First, a high-resolution Digital Surface Model (DSM) is generated using optical tri-stereo acquisitions. The DSM defines the topographic condition before the slope collapse. Secondly, a fast mapping of land cover changes is performed through satellite optical data. Finally, multi-temporal interferometric techniques are used to identify strong topographic variation on the Koitash slope after the collapse and small post event surface deformation affecting the crown area and the landslide deposits. Results highlighted the consequences of the landslide on diverting Mailuu Suu river path, highlighting a strong topographic variation due to the slope collapse. Moreover, ongoing surface deformations have been identified not far from tailings storage facilities containing radioactive deposits. The products are generated mainly from freely available satellite acquisitions, proving the capability of mapping and monitoring wide areas through a cost-effective approach.

Keywords

Mailuu Suu landslide • Radioactive waste tailings • DInSAR techniques • SBAS • Sentinel-1 • Digital surface model • Land cover changes • Landslide monitoring

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Introduction

Mailuu Suu valley, located in the southern border of Kyrgyzstan, Central Asia, is known for the dramatic environmental conditions due to the presence of the storage sites of uranium radioactive waste, resulted from the uranium mining and postprocessing completed in the late 1960s. Thousands of tonnes of uranium ore and processing waste are deposited all along this remote valley, in a definitely sensitive setting. In fact, tailings storage facilities are often located on weakly stable rocks and close to landslides-hazardous slopes (Torgoev 2008). Therefore, this context is creating an alarming environmental scenario that could lead to the contamination of the water supply for the Fergana valley, the most densely populated part of Central Asia. This is why this area is considered as one of the most polluted places in the planet. Numerous studies were carried out to analyse the main factors triggering landslides, as Golovko et al. (2017) did in South Kyrgyzstan, generating a landslide inventory for hazard assessment through remote sensing data, to facilitate an analysis at regional scale in case of information scarcity.

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Mailuu Suu area have been studied as some hundred landslides have affected the region in the last decades (Aleshin and Torgoev 2014). The recent re-activation of most of those paleolandslides has been influenced by mining activities and urbanization combined with geological and climatic main triggering factors. In this work, we focus on the re-activation of the Koitash landslide, affecting Mailuu Suu valley on the 28 April 2017. The landslide was characterized by a sudden and rapid kinematic and the total change of the slope surface. The rapid collapse of the slope caused the failure of a large amount of sediments, which accumulated just next to some of the tailing storage facilities containing radioactive wastes.

Landslide risk management is increasingly exploiting remote sensing techniques, often combining radar and optical remote sensing data, taking advantage of their multispectral characteristics, high revisiting cycle, wide area coverage and high spatial resolution (Metternicht et al. 2005). Several applications show how satellite acquisitions can support a detailed landslide inventory mapping. This can be address to prevention and disaster risk reduction activities but also to emergency response phase to estimate the event extensions, the caused damages and the ground motion situation and evolution (Casagli et al. 2016).

Here, we present an analysis of the post collapse condition of Koitash landslide. We integrated and combined different remote sensing techniques to analyse both optical and Synthetic Aperture Radar (SAR) satellite data. We performed a fast and automatic land cover mapping at large scale through Sentinel-2 data to detect the changes induced by the landslide; we generated a high-resolution digital surface model using tri-stereo optical data to define the slope topography before the event; finally we applied multi-temporal interferometric techniques on Sentinel-1 data, acquired after the event, to estimate the slope topographic changes after the collapse and the eventual ongoing deformation affecting the area. The choice of focusing on the post event allows avoiding the temporal decorrelation affecting the data before and after the collapse (Tessari et al. 2017). The benefit of the proposed approach is here presented, highlighting the cost-effectiveness, accuracy and scalability over larger areas towards an operational system

Study Area

Mailuu Suu valley is located in the western boards of Kyrgyzstan, in Jalal-Abad region (Fig. 1). This area is set in the tectonically and seismically active Tien Shan Mountains, affected by several strong earthquakes in the last century (Havenith et al. 2006). This area is known for the intense mining activities dedicated to radioactive uranium ore extraction, mainly between 1946 and 1968. In fact, in the framework of the Soviet nuclear program, around 9,100 tons of Uranium oxide have been produced. These activities have been abandoned later, as they were no more profitable. More than 23 unstable Uranium tailings storage facilities with unstable dams have been left by the Soviet Union on a tectonically unstable hilly area above the town. Nowadays, Mailuu Suu is one of the most polluted and radioactive places in the world. Moreover, the frequent occurrence of natural hazards, as landslides or floods, make this situation even more dramatic and dangerous.

This environmentally hazardous area was affected by a landslide, Koitash landslide, the 28th April 2017. This dramatic event caused the river blockage and the formation of a natural dam and the consequent migration of Mailuu Suu river, which is flowing at the bottom of the main slope (Fig. 2). The location of the unstable slope is shown in Fig. 3, where two optical satellite acquisitions allowed comparing the slope before and after Koitash landslide.

Methods

Several remote sensing analysis and processing techniques have been integrated in this study, focusing in several datasets and sensors. The conceptual analysis workflow is shown in Fig. 4, where blue boxes refer to the input datasets required to generate the maps (green boxes) and monitoring (yellow boxes) outputs.

More in detail, a high resolution Digital Surface Model (DSM) was generated from stereo or tri-stereo satellite optical data. The DSM was generated using the Space Stereo module of the Opticalscape© software, following a standard photogrammetric workflow. The generated DSM was used as reference for the two additional analyses steps, the Optical and the SAR data multi temporal analysis.

Satellite optical data were analysed to generate Land Cover Map (LCM), to verify the surface condition before and after the landslide event. The series of LCMs allowed identifying eventual changes induced by the slope collapse. The LCM were generated using Mapscape© software to download, process and extract the entire layer needed to be ingested into an own developed knowledge-based classifier. The LCM describes the area of interest in terms of settlements, vegetated area, dense forest, open land and bare soil.

The final steps of the workflow consist of the multi-temporal interferometric analysis of Synthetic Aperture Radar (SAR) data acquired with both ascending and descending geometry to retrieve surface deformation and estimate the collapsed volume. SAR datasets were analysed through the multi-temporal Small Baseline Subset (SBAS) technique (Berardino et al. 2002), implemented in the SARscape© software, to retrieve the evolution of deformations, highlighting potential accelerations, describing the

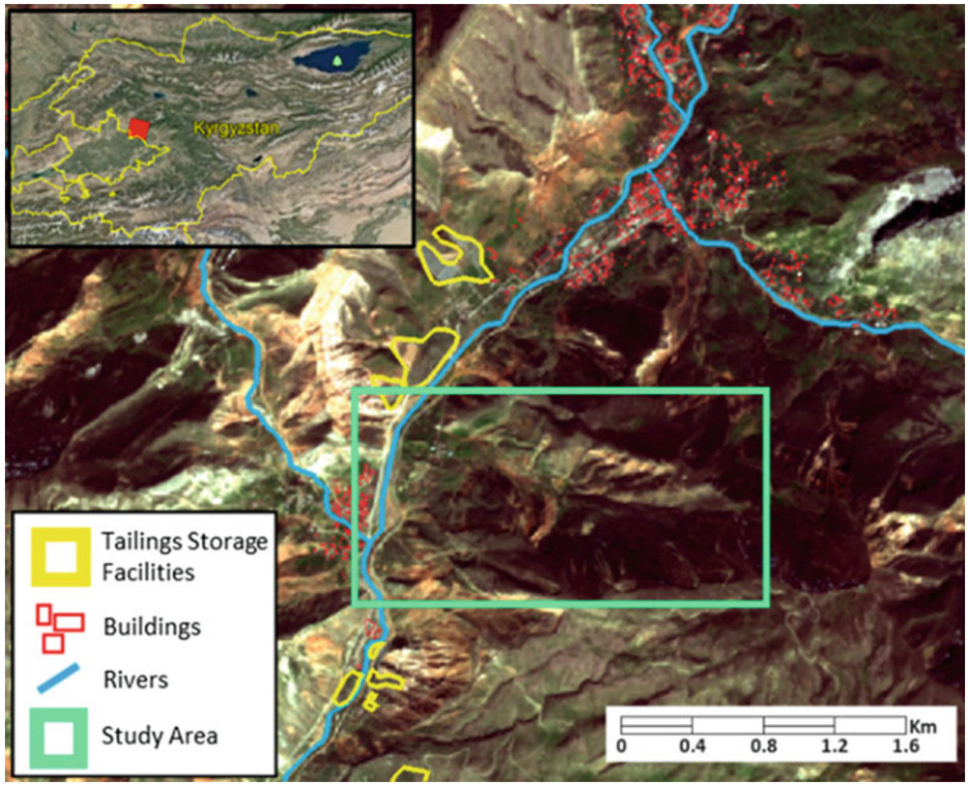

Fig. 1 Optical image of the slope affected by Koitash landslide (green box), showing the location of tailings storage facilities (yellow polygons), buildings (red polygons) and Mailuu Suu river (light-blue polyline)

Fig. 2 Photo of Koitash landslide few days after the collapse, showing the deviation of Mailuu Suu River

ongoing displacement and the potentially unknown instability phenomena affecting the area even after the 2017 collapse. The previously generated DSM was used as a reference in the SBAS processing. The SBAS was run using an intermittent approach, hence accepting some limited temporal decorrelations due to the vegetation seasonal changes, without losing the overall final information. Velocity and sequence of deformations obtained from the ascending and descending datasets were then combined and projected to obtain vertical and east-west velocity maps and time series of deformations, giving a more detailed information about the slope deformation directions. Moreover, the SBAS chain was calculating the topographic correction obtained from the SAR dataset respect to the reference DSM. The topographic variation was used to calculate the collapsed volume on the slope.

Data

The datasets selected and processed were identified trying to take advantage to freely available data. Only in case of the DSM generation, commercial Optical acquisitions were used as the highest resolution of the freely available ones is 30 m.

The DSM was generated from imagery acquired from the PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) system, a stereoscopic imaging instrument on-board the ALOS-1 satellite. The instrument provides

Fig. 3 Koitash landslide, located in Mailuu Suu valley, Kyrgyzstan. Satellite optical views of the study area before (left) and after (right) the landslide event. Red boxes identify the unstable slope (*Source* Google Earth)

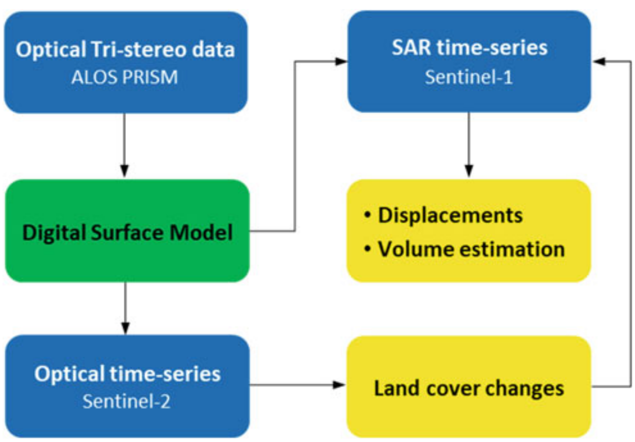

Fig. 4 Methodology conceptual scheme

tri-stereo along-track imagery with a ground sampling distance of 2.5 m at Nadir and a Swath Width of 35 km. The images were acquired in May 2008. The generated DSM has a 5 m resolution. This product is one of the most cost-effective available stereo data, considering their resolution and the cost per square km.

The LCM before and after the landslide event were generating using the freely available Sentinel-2 data. Sentinel-2 data are EC Copernicus spaceborne multi-spectral optical acquisitions, at 10 m resolution. The images were acquired pre and post event, respectively on the 9th April 2017 and on the 8th June 2017.

The multi-temporal SAR interferometric analyses was focused on the freely available Sentinel-1 acquisitions. This EC Copernicus mission provided dense stacks of SAR images, acquired with two different geometries, along ascending and descending orbits, with a 15 m resolution and a 12-day revisiting time. In particular, the analyses considered the post event time period, using the data acquired after the slope collapse, from July 2017 up to January 2020. The analysed datasets consist in 77 ascending images (track 100) and 76 descending images (track 5).

Results

The LCMs generated from Sentinel-2 data are shown in Fig. 5, where black boxes highlight the pre and post landslide condition. Most of the slope, classified as vegetated area and dense forest before the event, changed into bare soil after the collapse. In particular, bare soil on the slope toe corresponds to the collapsed material. The river path was deviated of approximately 120 m because of the landside, causing possible inundation risks for the surrounding inhabited areas. First results allowed to fast mapping large areas, identifying the landslide effects from the land cover variation.

The high-resolution DSM generated from PRISM data extends over 35 × 35 km^2 area. This output has been used as reference topographic layer during the Sentinel-1 SBAS processing. Respect to the existing freely available low resolution DSM, working with a high resolution DSM was helping on estimating and removing the topographic component from each interferogram phase difference, reducing the presence of topographic residual fringes and facilitating the unwrapping step. Moreover, the PRISM DSM refers to 2008 acquisitions, before the landslide event, while

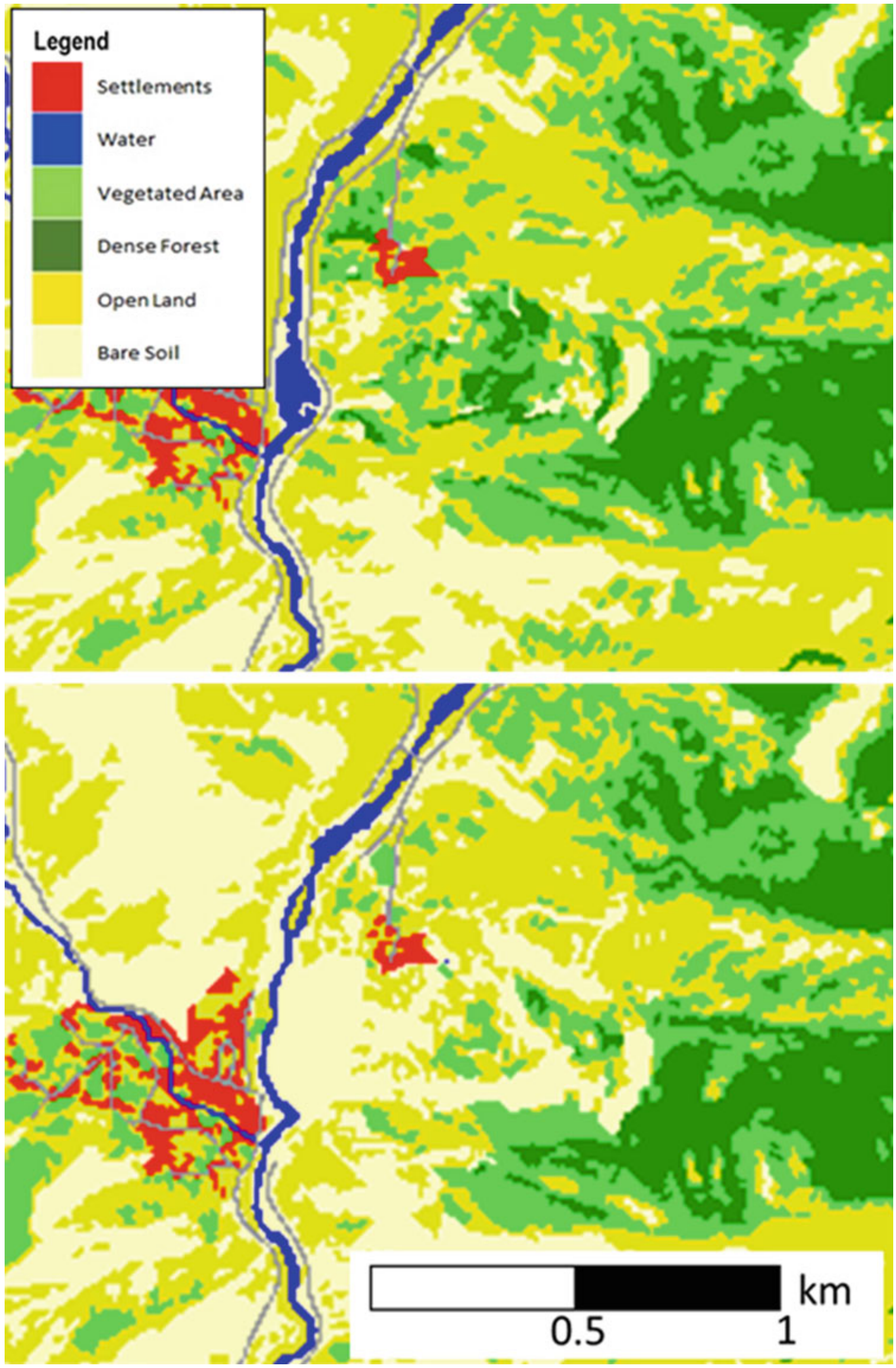

Fig. 5 Land cover maps before (above) and after (below) the Koitash landslide, collapsed the 28 April 2017. Black boxes identify the slope affected by the landslide. Comparison shows the variation of the river flow and increasing of bare soil due to mass movements

Sentinel-1 data span the period 2017–2020, hence a post landslide period. As a consequence, the topographic correction obtained from the SAR data, as one of the output of the SBAS process, measured the dramatic slope morphological change induced by the landslide. In fact, negative elevation corrections obtained in the landslide crown area and the upper part of the slope, correspond to an elevation reduction because of the material collapse. On the contrary, the lower part of the slope was interested by the sediment accumulation, leading to an increase of the elevation, and therefore a positive elevation correction. These results are shown in Fig. 6, where the red polygon highlights the landslide while the red segment shows the A-A′ cross-section which provides the elevation correction along the slope. The A-A′ profile in Fig. 7 shows a maximum sediment accumulation of almost 15 m, while, the depth of the sliding surface in proximity of the crown area is around 30 m. The collapsed along the scarp caused a downward displacement of 4.7 million m^3, as calculated directly from the topography correction in Fig. 6. Moreover, the accumulated material covers the original river path, in agreement with the LCMs in Fig. 5. Additionally, results obtained from Sentinel-1 provide the ongoing deformations affecting the slope after the landslide event. Mean rate of deformation maps, projected along the vertical and east-west directions, are shown in Fig. 8, where the red polygons identify the Koitash landslide.

The deformation colour scale ranges from blue to red, corresponding to subsidence/compaction and uplifting in case of vertical displacements, while in the horizontal

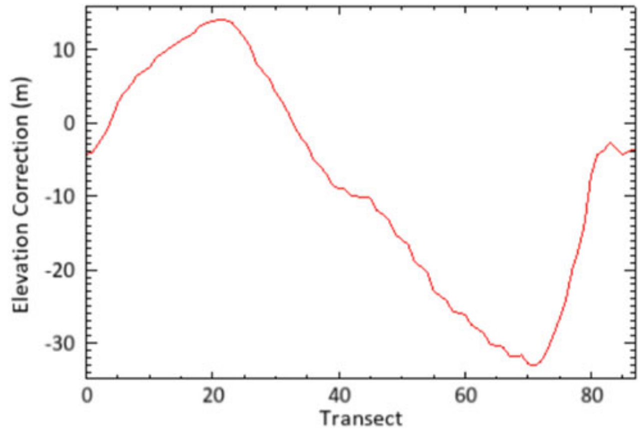

Fig. 7 Cross section of the elevation correction, respect to the reference DSM obtained from PRISM data (2008), obtained from SBAS multi-temporal processing of Sentinel-1 data acquired between 2017 and 2020. The location of the profile is shown in Fig. 6 and it is represented with a red segment

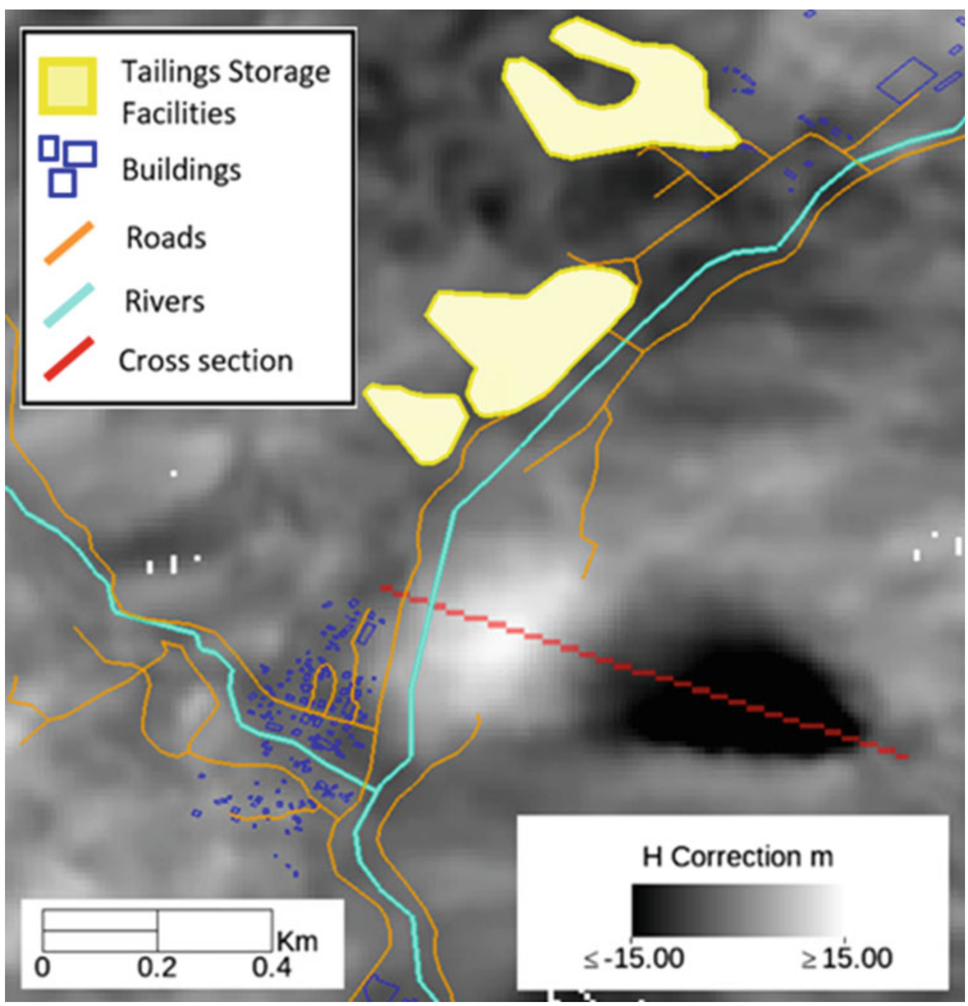

Fig. 6 Elevation correction, respect to the reference DSM obtained from PRISM data (2008), obtained from SBAS multi-temporal processing of Sentinel-1 data acquired between 2017 and 2020. The red polygon highlighted the Koitash landslide

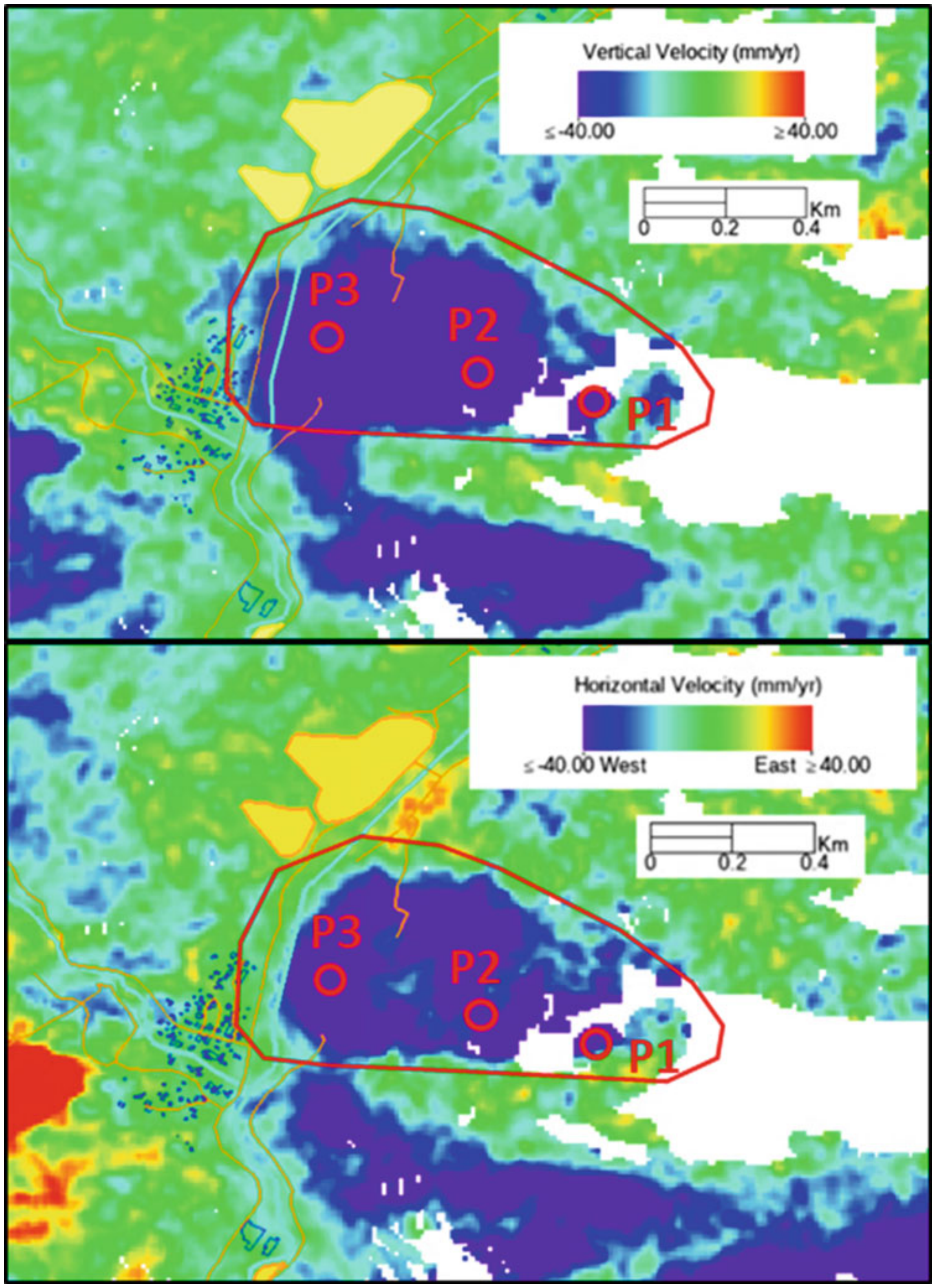

Fig. 8 Vertical (above) and East-West (below) mean velocity maps obtained from the processing of Sentinel-1 data acquired between 2017 and 2020. The red polygons identify the location of the landslide. Yellow polygons correspond to the radioactive tailing store facilities

deformation map, blue areas are moving westward, while red areas are moving eastwards, depending on slope aspect. Results in Fig. 8 show how the slope is clearly affected by vertical deformation as well as an ongoing horizontal displacement along the west direction, both with a rate overcoming 40 mm/year.

Three points along the slope have been selected in Fig. 8. Vertical and east-west time series of deformations are plotted (Fig. 9). It is possible to notice how the crown area is more affected by horizontal deformation than vertical ones, while both the central part and the toe of the slope are showing a higher vertical component. In addition, P2 and P3 are characterized by an almost constant linear trend of deformations, while P1 is showing an initial stability followed by an acceleration, more evident in the vertical component. This describes a re-activation of the deformation some months after the landslide. Moreover, the area affected by ongoing deformation is extending close to the tailing storage facilities, identified by the yellow polygons in Fig. 8, that is located at approximately 200 m far from the collapsed slope.

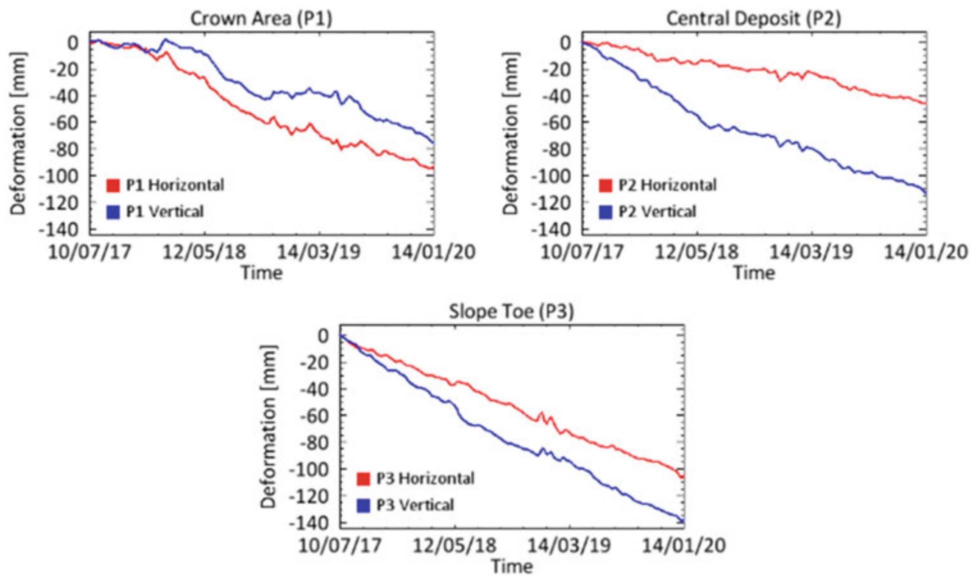

Fig. 9 Horizontal (red curves) and vertical (blue curves) time series of deformations plotted in P1, P2 and P3, located at the crown area, the central portion and the toe of the slope obtained from the processing of Sentinel-1 data acquired between 2017 and 2020. The location of points is shown in Fig. 8

Concluding Remarks

This study analysed the post event condition of Koitash landslide, located in Mailuu Suu area, integrating different remote sensing techniques to highlight the potential of this methodology in case of disaster management, prevention or intervention.

One of the main advantages of the proposed workflow is the capability of providing information over large areas, reducing any possible risk related to field monitoring, particularly relevant after a landslide collapse. In fact, a first fast mapping of satellite optical data allowed identifying the portion of the slope affected by the landslide and tracing the deviation of the Mailuu Suu river path. The generation of a 5 m resolution DSM supported the definition of the topography before the Koitash failure. Moreover, from interferometric SAR data it was measured the ongoing sliding trend, compaction and deformation affecting the slope even after the failure. The landslide crown area re-activated in the spring 2018, one year after the collapse, probably because of the seasonal rainfall events. The lower part of the slope is affected by constant deformation rates after the collapse, probably related to the compaction of the collapsed sediments. The topographic correction in respect to the reference DSM retrieved the morphology and elevation changes due to the landslide giving the necessary information to estimate the displaced volumes. Therefore, despite Sentinel-1 mission has been mainly designed to monitor deformations, results show how the multi-temporal and redundant generation of interferograms having multiple normal baseline values could provide useful information in respect to the topographic changes too.

Future developments of the work could focus on searching for precursor deformations affecting the slope before its collapse. In addition, despite the presented results focused on Koitash landslide, the study was conducted on a much larger area. In fact, taking advantage of the spatial coverage of the generated DSM and the freely available Sentinel-1 and Sentinel-2 datasets, it was possible to extend the proposed analysis to an area, which extends approximately 35×35 km^2. Over the full extension of the analysed data, several slopes showed ongoing deformations and the topographic changes indicated numerous collapses occurred between 2008 and 2017.

Considering the high environmental sensitivity of all Mailuu Suu valley, because of the numerous radioactive material storages, being able to identify even small deformations and dramatic topographic changes, is allowing to have a clearer idea of the most hazardous areas and their proximity to the uranium deposits. In this context, the proposed methodology demonstrated its cost-effectiveness and proved to be a powerful mapping tool to identify and quantify on-going processes in hazardous sites were additional ground measurements are required or where to install monitoring instrumentation.

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