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Landslide Monitoring in the Main Municipalities of Sikkim Himalaya, India, Through Sentinel-1 SAR Data

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Abstract

Landslides are a large threat that generate important damage, economic losses and human fatalities worldwide. Identifying terrain deformations related to these phenomena is critical to reduce their impact. In particular, the population of the Indian Himalayas are menaced by landslides, which regularly endanger villages and vital transport axes. Here we present the monitoring of instabilities on some urbanized areas of Sikkim State testing the capabilities of Remote Sensing techniques, and particularly Multi-temporal analysis of Synthetic Aperture Radar data. The main municipalities of Sikkim State have been analysed, covering the most inhabited areas where landslide effects could be more dramatic for the local population. We illustrated the results obtained over the capital, Gangtok, and Namchi. These cases have been analysed thanks to the global availability of Sentinel-1 SAR data. The main multi-temporal interferometric techniques have been applied, Small Baseline Subset (SBAS) and Persistent Scatterers (PS) depending on the extension and density of the urban areas. These techniques allow to map and measure surface deformations with a millimetre sensitivity, providing the temporal evolution of the deformation trends. This is fundamental to identifying activation/re-activation of landslides and analyse eventual correlation with external factors. In case of Gangtok, a strong relation with the rainy season was easily identified. Advantages and limitation of these techniques in such arduous areas are discussed.

Keywords

Sikkim Himalaya • Landslide mapping • Multi temporal InSAR • Sentinel-1

Introduction

Landslides are a large threat to the population of the Indian Himalayas and regularly endanger villages and vital transport axes. Landslide incidences have been of serious concern to the societies of the affected regions because of their potential to cause the loss of life, deteriorate natural resources, damage infrastructural facilities, etc. According to a Geological Survey of India study, 12.6% of India's landmass falls under the landslide-prone hazardous zone and 8% of global landslide fatalities are reported from our country. Out of the total land area prone to landslide, 0.18 million sq km fall in the northeast Himalayas, including Darjeeling and Sikkim. Naithani (1999) has estimated that damages caused by landslides in the Himalayan range cost, on average, more than one billion US dollar per year, besides causing more than 200 deaths every year. Only in 1968, more than 33,000 fatalities were reported in Sikkim because of landslides (Choubey 1992). In the light of these numbers, it is evident that the monitoring of surface displacements and landslide movements becomes an important task.

Traditionally, landslide hazard assessment had to be carried out on-site, relying on ground-based methods (Bhasin et al. 2002). Largely field-based approaches are often made arduous by high risk exposure, as well as observational biases towards objects in easily accessible areas. Observable target areas are local to maximally sub-regional. Due to the large number and extent of the landslide prone areas in the Himalayas ground-based methods are not suited for rapid detection and monitoring of hotspot areas. Remote sensing approaches, on the other hand, enable objective, safe, and spatial continuous observations at different spatial

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scales, covering large areas. Recently, studies focused on landslide susceptibility estimation have been performed on Sikkim cities, e.g. on Gangatok (Kaur et al. 2019). Despite several studies carried out at landslide prone areas, there is lack of in depth scientific study to map the temporal evolution of surface deformation affecting the main municipalities and urbanized areas.

Starting from the Nineties, Space-borne Synthetic Aperture Radar (SAR) data demonstrated to be an effective tool to monitor surface deformations affecting soil, structure and infrastructures. Numerous works were focus on the use of SAR data for detecting and monitoring landslides, clarifying their potentially and limits (Wasowski and Bovegna 2014; Barra et al. 2016; Béjar-Pizarro et al. 2017; Tessari et al. 2017a). Actually, despite numerous successful applications, it is fundamental to consider data decorrelation, which typically affect dense vegetated slopes, layover, shadow and signal distortions due to the acquisition geometry of SAR data and the limitations on the maximum detectable deformation velocities (Cascini et al. 2009). In detail, maximum detectable LOS deformation between two adjacent scatters cannot exceed $\lambda/4$ within one revisiting time interval to prevent ambiguity of phase measurements Therefore, generally slow landslides can be detected while fast kinematic ones, as debris-flow as rock falls cannot be analysed through Interferometric techniques. Some alternatives, as change detection approach, can be used to map fast surface changes (Tessari et al. 2017b). The perspective of landslide detection, mapping and characterization is expected to increase thanks to a new generation of SAR data, Sentinel-1, currently acquired by the European Space Agency, which guarantees a continuous monitoring, covering all over the world surface at least once every 12 days.

Considering the alarming situation daily faced on the main Sikkim municipalities, the Cooperation Office of the Swiss Embassy (SDC) located in New Delhi has been supporting several projects aimed on using new and advanced technologies to provide the necessary information for risk mitigation in the Himalayan Region s in the framework of the action "Strengthening State Strategies for Climate". In fact, the outcomes of the present work have been provided to the Sikkim State Disaster Management Authority (SSDMA).

Fig. 1 Location of the Indian Himalayan state of Sikkim and its main regions, North, West South and East Sikkim with the respective capitals (left side). Satellite optical map of Sikkim (right side)

Study Areas

Sikkim, an Indian small mountainous state in the eastern Himalayas, located between Nepal, Tibet and Bhutan, covers an area of 7069 sq. km. It is also a hilly state consisting of tangled series of interlocking mountain chains rising range above range from the south to the foot of high peaks, which marks the snow line in the north. The state has four districts East District, West District, North District and South District with their headquarters at Gangtok, Geyzing, Mangan and Namchi respectively (Fig. 1). Sikkim has a very rugged topography and formidable physical features. The whole state is enclosed on three sides by lofty ranges and spurs of Greater Himalaya with varying heights on three sides. Within Sikkim, the main municipalities and villages are almost entirely within the Lesser Himalayas, consisting mainly Daling group of rocks which have undergone several episodes of loading, unloading and uplift during the orogeny. The result is a hazardous combination of weak geology (micro-fractures, joints, fissures, separated foliation planes, faults etc.) and high relief within short distances. The main causative factors of slope instability are weak geology, adverse planar structures in rocks, unstable slope materials, steep slopes or high relative relief. Moreover, intense rainfalls cause surface runoff of water, despite man-made drains are trying to reduce the landslide risk.

In the framework of this project, the main Sikkim municipalities have been analysed: Gangtok, Namchi, Geyzing, Pelling, Soreng, Sombaria and Mangan. Here we present the results of only two cases among these cases: Gangtok, the densely urbanized capital of Sikkim, and Namchi, as representative of all the other cases, characterized by a sparse, low-density urbanisation.

Data and Methods

Sentinel-1 is a Copernicus programme satellite constellation run by the European Space Agency, through a constellation of two polar-orbiting satellite where C-band radar for SAR applications are installed. Two dataset are available over Sikkim, respectively acquired by Sentinel-1 satellite while is flying from South to North (ascending orbit) and from North to South (descending orbit). The main characteristics of the two datasets are described in Table 1.

Table 1 Main characteristics of Sentinel-1 SAR datasets analysed over Sikkim main municipalities

	Acquisition geometry	
	Ascending	Descending
Relative orbit	12	48
Number of Scenes	79	90
Time interval	Mar 15—Sep 18	Oct 14—Sep 18
Revisiting time	12 days	
Resolution	15 m × 15 m	

SAR data record the back-scattered signals of ground surfaces and soil targets. SAR Interferometry consists of the analysis of the phase difference between two SAR images referred to equivalent areas, i.e. relative to the same frame observed from different points of view.

One of the component of the obtained phase difference is due to possible ground deformations, that can be isolated through the unwrapping of the phase difference, the so-called Differential InSAR (DInSAR), to create displacement and velocity maps and identify hazardous phenomena.

Beside the conventional DInSAR, two additional complementary approaches can be used for the measurement of the temporal evolution of deformations. One is the Persistent Scatterers (PS) (Ferretti et al. 2001) and the other is the Small Baseline Subset (SBAS) (Berardino et al. 2002) technique. PS relies on strong stable point scatterers (such as rock or man-made structures) while the SBAS is intended for the analysis of distributed targets. With respect to the PS, the SBAS technique is less sensitive to the number of acquisitions, because it exploits the spatially distributed coherence, instead to exclusively consider single points, as in the PS. However, in general, it is worth mentioning, that the more the acquisitions, the better the resulting product quality because the atmospheric component can be better estimated and reduced. Concerning the displacement, with respect to the PS technique, which is limited to the linear behaviour, the SBAS one can estimate quadratic and cubic models. Moreover, no modelled displacements are derived. On the maximum displacement, while there is no constraints in temporal term, the displacement is limited with respect to the spatial variability, due to the phase unwrapping. In addition, the SBAS approach is more robust than the PS one, because it takes advantage from the higher redundancy of all available cross-interferograms. Depending on each case, the most adequate multi-temporal InSAR algorithm is applied. The availability of two acquisition geometries allows retrieving deformation not only along the satellite Line of Sight (LOS) but also to project the results along the vertical and east–west directions.The main challenges with capturing landslides using these methodologies are both dense vegetation and strong topography, which have a negative impact on the radar signal to properly detect ground movements that could be identified as landslides. These challenges might be more easily addressed in the low density urbanized municipalities, generally located on the top of hills and mountains, as it happens for the considered cases.

Results

The main results obtained over Namchi and Gangtok consist on the mean velocity maps of deformation (Fig. 2) and the time-series of deformation (Fig. 3), available for each pixel covered by the final results, measured along the satellite LOS. For all the study areas, both ascending and descending data have been analysed with PS technique. Therefore, it was theoretically possible to combine the ascending and descending LOS velocity to obtain the vertical and east–west component of deformations. Nevertheless, the composition is possible only for those pixels where the results are available for both the acquisition geometries.

In the considered cases, the dense vegetation and the topographic conditions limited the spatial coverage of the results and the possibility of combining and project the LOS results.

The mean velocities maps of Namchi are shown in Fig. 2 where green points are stable, blue ones are moving far from the satellite while red points are moving towards the satellite with a maximum velocity rate up to 10 mm/yr. In particular, Fig. 2 highlight a portion of a slop oriented West-Est, where the deformation for the ascending and descending datasets are respectively positive and negative, compatibly with the different satellite acquisition geometries. The corresponding time series of deformations are shown in Fig. 3. The different LOS deformation rates are due to a horizontal deformation rate eastwards and a downward component too.

Only in the Gangtok area, also the SBAS technique has been applied thanks to the spatially distributed coverage of the results allowing the projection of deformation velocities and their temporal evolution along the vertical and east–west directions. The total vertical displacements are shown in the left panel of Fig. 4, where blue areas are moving downward. Results highlight that several slopes are affected by deformation exceeding 60 mm in the analysed period (October

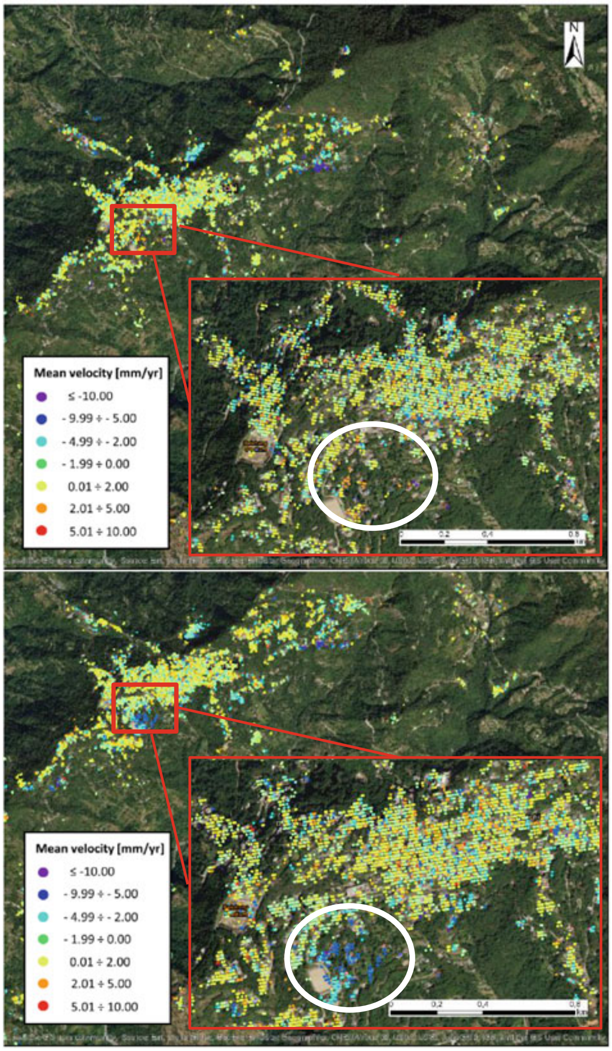

Fig. 2 Line-of-sight mean velocity map of deformation of Namchi obtained through PS technique applied to the Sentinel-1 descending (above) and ascending (below) datasets (time interval October 2014—September 2018). Blue areas are moving far from the satellite, green areas are stable while red areas are moving toward the satellite. The red box show a zoom of an area affected by a landslide

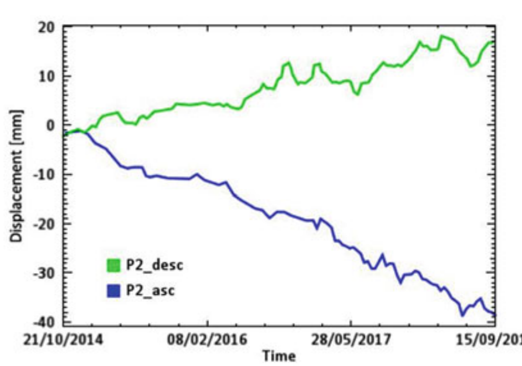

Fig. 3 Time series of deformation of a point selected on the area affected by deformation (inside the white circle in Fig. 2)

2014—September 2018), both on slopes oriented to East and West, on Gangtok city. Horizontal deformations are represented in the right side of Fig. 4 with westward displacements in blue and eastward in red. A significant point have been selected to analyse the behaviour of the ongoing deformations. Figure 5 shows the vertical time series of deformation (red curve) which is characterized by some acceleration and deceleration interval showing a seasonal behaviour. We search a possible correlation between the oscillation affecting the time-series of deformation and the rainfall seasonal distribution. We analysed the cumulative monthly rainfall measured in Gangotok area. Results of the comparison between temporal evolution of deformation time-series and the monthly cumulative rainfalls are presented in Fig. 5.

Comparing the red line, corresponding to the deformation trend, and the blue curve showing the monthly rainfall, it is possible to identify a strong connection between the increasing amount of monthly rainfall (from April/May to August) and an acceleration of the deformation trends, where the maximum gradient correspond to the rainfall peaks, while flat behaviour of the deformation occur in the dry season.

Discussion and Conclusions

The present project has been focused on mapping landslide affecting the main Sikkim municipalities through the capabilities of space-borne Synthetic Aperture Radar (SAR) data

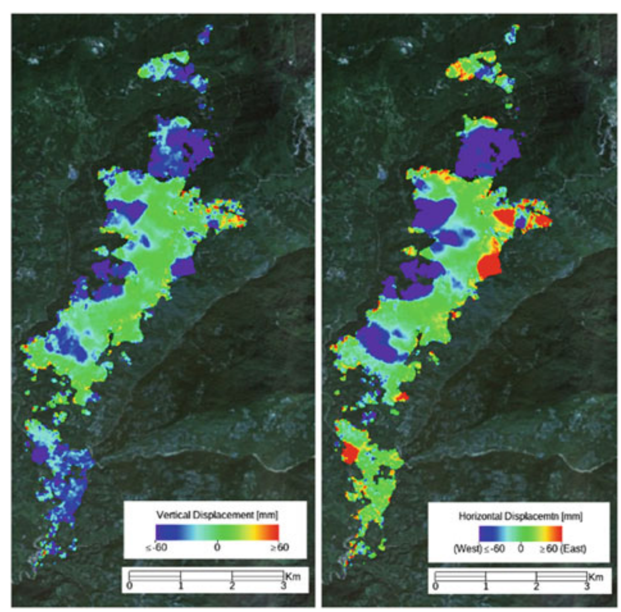

Fig. 4 Vertical (left) and East–West (right) velocity map of deformations of Gangtok obtained through SBAS technique applied to the Sentinel-1 datasets (October 2014—September 2018). Green areas are stable in both the maps, blue areas are moving downwards in the left map and westward in the right one. Red areas in the right frame are moving eastwards

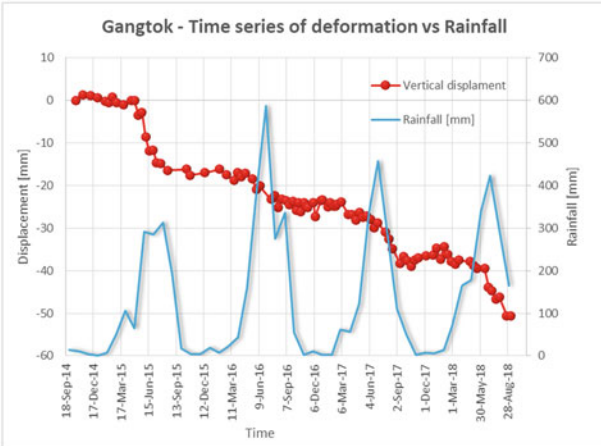

Fig. 5 Vertical time-series of deformation of a selected point in Gangtok area (red line) compared to the cumulative monthly rainfall (light-blue curve)

on monitoring surface deformation. The illustrated analyses have been performed through the processing of Sentinel-1 SAR data, freely available SAR data acquired in the framework of a Copernicus project. All the deformation maps of Gangtok, Namchi, Geyzing and Pelling, Soreng, Sombaria and Mangan have been provided to the SSDMA and here two representative case of Namchi and Gangok have been shown.

They main multi-temporal interferometric techniques, PS and SBAS have been applied to two stacks of data, acquired with two different satellite orbits, ascending and descending. For all the datasets, PS analyses was performed, allowing retrieving information only over the small building and houses widely spread on the mountainous/hilly areas. Because of the localized information, strongly related to the satellite acquisition geometries, the deformation maps obtained from the two datasets are characterized by results overlapping only partially. To avoid losing information, the projection along the vertical and east–west components has not been performed, preferring to extend as much as possible the mapped information.

Only in the case of Sikkim capital, Gangtok, additional analyses have been performed using SBAS technique and the satellite LOS results have been combined to obtain the vertical and east–west components of displacement.

SBAS processing chain showed some restrictions on being applied in Namchi (as well as in all the other municipalities), because of the low density of buildings, generally quite spread and distributed on different crests. This municipality structure is limiting the spatial distribution of detectable targets, creating discontinuities on coherent area on the data processing, and consequently, limiting the SBAS applicability.

Nevertheless, PS technique was able to identify the localized area affected by deformation, possibly connected to landslide characterized by slow dynamics.

Interesting results have been obtained on Gangtok area. In fact, Sikkim capital is definitely the most densely urbanized municipality of Sikkim. This is a favourable condition as it is guaranteeing a backscattered SAR signal stable in time. Consequently, the spatial coverage of the results obtained in Gangtok is much more extended and continues than in the other selected municipalities. Moreover, the good coverage obtained in both the ascending and descending processing allowed combining the results of the two datasets, and project the measured time-series of deformation along the horizontal and vertical directions, providing an additional information related to the direction of the real displacements. The great power of this technique on retrieving the temporal evolution of deformations is particularly interesting as this allows to identify variable trends, acceleration and oscillation, supporting a post-processing stage of result interpretation, trying to identify a correlation with triggering factors.

In the case of Gangtok, an attempt of identify a relation between rainfall season and sliding acceleration has been performed. This analysis showed a strong correlation between monthly rainfall and variation of the deformation behaviour.

Anyway, because of the highly vegetated land surface, the intense rainy season and the seasonal or permanent snow cover, these techniques show their limitation on detecting landslides and deformation in non-urbanized areas.

Nevertheless, some of the limitation could be overcome according to the following observation. Vegetation variation is strongly dependent on seasonal and weather conditions. Therefore, data temporal decorrelation could be more intense during wet seasons than during dry seasons. As a consequence, a possible improvement on the data processing, focused on increasing the spatial coverage of the deformation velocity maps, could be obtained selecting only data acquired during the dry season. Moreover, sensor wavelength, depending on the acquisition band, can strongly influence the sensitivity to surface variation, generally on vegetated surfaces. The capability of penetrate vegetation of radar data is increasing as the wavelength increases. Therefore, using L-band data instead of C-band ones (as Sentinel-1) could help on reducing the sensitivity of vegetated surface changes and the consequent temporal decorrelation. At the moment, the only available space-borne L-band SAR data are ALOS Palsar-2, acquired by JAXA. The main limitation of these data is the poor revisiting time, theoretically 14 day but the acquisition plan is not very dense around the work and there are long temporal gaps, where data are available. The previous point will be solved once the new NASA-ISRO SAR mission, NISAR, will be launch. NISAR will acquired L-band SAR data (and S band only over India), with a world coverage, a revisiting time of 10 days, guaranteeing a constant availability of data. Once this mission will be operational, the applicability of the proposed multi-temporal

DInSAR techniques on vegetated areas will dramatically increase. Finally, more detailed and resolute information could be obtained on urbanized areas, buildings, streets and infrastructure, considering higher resolution X-band SAR data, as the ones acquired by COSMO-SkyMed, TerraSAR-X and PAZ missions. These acquisitions are characterized by a 3 to 1 m resolution, enabling to obtain a much detailed information on the stable scatterers.

All the generated velocity maps should prove their essential value on defining and installing landslide ground monitoring system, identifying and limiting the most dangerous areas. Moreover, thanks to the correlation between slope acceleration and rainfalls, this data could help on setting and calibrating some alert systems based on rainfalls (Floris et al. 2013). Eventually, these data could be used as a reference monitoring system itself, planning to continuously updates the temporal evolution of deformation, every time that a new Sentinel-1 scene is acquired over the study area (Béjar-Pizarro et al. 2017), consciously that, despite dealing with slow landslide, the 12 day revisiting time could not be able to catch in time an eventual acceleration of the slope. Therefore, the integration with future incoming SAR mission will also help on increasing the frequency of SAR measurements in case of monitoring applications.

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