Application of Persistent Scatterer Interferometry (PSI) in monitoring slope movements in Nainital, Uttarakhand Lesser Himalaya, India

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Orogenic movements and sub-tropical climate have rendered the slopes of the Himalayan region intensely deformed and weathered. As a result, the incidences of slope failure are quite common all along the Himalayan region. The Lesser Himalayan terrane is particularly vulnerable to mass-movements owing to geological fragility, and many parts of it are bearing a high-risk of associated disaster owing to the high population density. An important step towards mitigation of such disasters is the monitoring of slope movement. Towards this, the Persistent Scatterer Interferometry (PSI) technique can be applied. In the present study, the PSI technique is employed in Lesser Himalayan town of Nainital in Uttarakhand state of India to decipher and monitor slope movements. A total of 15 multi-date ENVISAT ASAR satellite images, acquired during August 2008 to August 2010 period, were subjected to PSI, which revealed a continuous creep movement along the hillslopes located towards the eastern side of the Nainital lake. The higher reaches of the hill seem to be experiencing accelerated creep of ~21 mm/year, which decreases downslope to ~5 mm/year. Based on spatial pattern of varying PSI Mean LOS Velocity (MLV) values, high (H), moderate (M), low (L) and very low (S) creeping zones have been delineated in the hillslopes. Given the long history of mass movements and continuously increasing anthropogenic activities in Nainital, these results call for immediate measures to avert any future disaster in the town.

Keywords. Slope instability; landslide; Lesser Himalaya; remote sensing; radar interferometry.

1. Introduction

Continuing tectonic movements have rendered the entire Himalayan Range highly deformed, criss-crossed with numerous penetrative weak planes, and thereby made its slopes highly instable. In general, all the four major lithotectonic units of the

Himalaya, viz., *Tethys Himalaya*, *Great Himalaya*, *Lesser Himalaya* and *Siwalik*, are prone to slope failure and mass movements. The proneness of slope failure, however, varies spatially, depending on a number of factors, such as geology, land use/land cover, soil, precipitation, anthropogenic interventions, etc. Nevertheless, the risk of slope

failure induced disasters is highest in the Lesser Himalaya, as it is the most populous terrane of the Himalaya, having large townships like Shimla, Mussoorie, Nainital, Pithoragarh and Gangtok in Indian Himalaya, and Kathmandu and Pokhara in Nepal Himalaya.

The mass movements and slope instabilities of the Lesser Himalaya have been investigated for nearly past one-and-a-half centuries (e.g., Oldham 1880; Middlemiss 1890; Auden 1942; Srivastava 1968; Valdiya 1988; Bartarya and Valdiya 1989; Mathew *et al.* 2009). A number of studies have been conducted and landslide hazard zone maps of different parts of the Lesser Himalaya have been prepared (e.g., Gupta *et al.* 1999; Dahal *et al.* 2008; DMMC 2011, 2013; Anbalagan *et al.* 2015). A crucial issue often eluded in this context is the monitoring of slope movements, probably due to cumbersome and time consuming field techniques. The present study is aimed at prognosticating the slope instability in Nainital town in Uttarakhand state of India by monitoring slope movements through application of state-of-the-art space-borne

remote sensing technique of Synthetic Aperture Radar Interferometry (InSAR) (figures 1 and 2).

The inhabited hillslopes of Nainital are known to be instable (see DMMC 2011 and references therein). The town has suffered loss of life and property due to mass movements in 1867, 1880, 1893, 1898, 1924, 1967, 1989 and 1998. The most disastrous of these landslides occurred on 18th September, 1880, along the southwestern slopes of the Snow-View Hill (aka Alma Hill). It took a toll of 151 people and completely damaged many buildings. Enormous debris generated by this landslide filled some part of the lake and converted it into a semi-flat ground (indicated as 'Flats' in figure 2). Later, in 1967 one more landslide occurred on the southwestern slope of the Sher-ka-Danda ridge. Furthermore, several studies have identified the Sher-ka-Danda ridge as highly-to-moderately landslide prone or highly-to-moderately unstable (Hukku *et al.* 1974; Sharma 1981; Valdiya 1988; DMMC 2011).

As a matter of fact, the entire northwestern–northeastern part of Nainital town is located on

Figure 1. Major lithotectonic terranes of the Himalaya in Uttarakhand. ITS: Indus Tsangpo Suture; STD: South Tibetan Detachment; MCT: Main Central Thrust; MBT: Main Boundary Thrust; HFT: Himalayan Frontal Thrust.

Figure 2. Google Image showing Nainital Township, Uttarakhand state of India.

the coalesced landslide debris fans, originating from the Naina and Sher-ka-Danda ridges (figures 2 and 3). Despite that a number of investigations have long been aimed at understanding various aspects of slope instability, the slope movements in Nainital have not been monitored for the past nearly five decades (Valdiya 1988; DMMC 2011). In the past, from the year 1895 to 1979, slope movements in the town were monitored using theodolite measurements of specially constructed pillars and pegs, which revealed spatial and temporal variability in slope movement. However, the discontinuation of these measurements in 1979 has resulted in huge data gap and thus the present rate of slope movement in Nainital is not known. The absence of such a crucial data would inflict every effort of analyzing the town's proneness, vulnerability and risk to mass movement induced disasters. Admittedly, the monitoring of slope movements in Nainital is called for, as also in other inhabited areas of the Himalaya. However, the unabated, long-term monitoring of slope movement would demand a

hassle-free, less tedious, time saving and accurate technique.

Keeping in view of the above, the present study is taken up in a pilot mode to test the feasibility and applicability of a satellite remote sensing based InSAR technique in quickly and accurately measuring and monitoring slope movements in the Himalayan terrains. The InSAR techniques are hassle-free, less tedious, and quick in delineating any sort of surface deformation in multitemporal domain and hence could be used for monitoring slope movements in the Himalaya.

2. Geological setting

Nainital is located in the southeastern extremity of the Krol Belt of the Lesser Himalaya (Auden 1934). Occupying the core of a faulted, doubly-plunging large syncline, the rock succession of Nainital town belongs to Krol and Tal formations of Neoproterozoic–Lower Cambrian ages (Auden

Figure 3. Past incidences of mass movements depicted on the geological map of Nainital (compiled and modified after DMMC 2011).

1934; Singh and Rai 1983; Pant and Goswami 2003) (figure 3). The rocks of the larger part of the town belong to the Neoproterozoic Krol Formation. The most accepted lithostratigraphy of the Krol Formation is based on an informal scheme proposed by Auden (1934), which subdivided it in an ascending order as the Lower Krol, Middle Krol and Upper Krol sequences. The Lower Krol sequence comprises thinly bedded, sheared, variegated slates, and marls with subordinate bands and lenses of dolomite. The Middle and Upper Krol sequences comprise dolomites and red slates. The overlying Tal Formation comprises carbonaceous pyritic slates with subordinate dolomite, mudstone and sandstone; it is exposed only on the hills tops in the west of the Naini Lake (Sharma 1981; Valdiya 1988). The sedimentary sequence of the area is intruded by a few dolerite dykes (figure 3).

The rocks in and around Nainital are sheared, jointed, folded and cut by a number of local faults. All the faults in the area are considered to be tectonically active (Valdiya 1988; Hashimi *et al.* 1993). The most prominent structural entity of the area is the NW–SE trending Nainital Fault, movements along this fault is implicated for the formation of the Naini Lake (Valdiya 1988). This Nainital Fault separates the Lower Krol sequence of the Sher-ka-Danda ridge, in the east of the Naini Lake, from Middle–Upper Krol sequence of the Ayarpatta ridge, in the west of the Naini Lake (figure 3). The rocks of the area have four sets of joints that are steeply (35° – 75°) dipping towards NE, SE, SW and NW (Sharma 1981). Furthermore, the Sher-ka-Danda ridge is also traversed by three prominent fractures (figure 3).

Geomorphically, the township of Nainital is developed in an amphitheater-like valley, enclosed

by high ridges on its eastern, northern and western sides (figure 3). There are large aprons of old landslides along the northern and northwestern foothills. As already pointed out, a large part of the town's settlement is developed on these old landslide debris.

3. Data and methodology

The present study is based on an InSAR technique, in which the phase difference between two or more SAR (Synthetic Aperture Radar) images is used to detect surface undulations/deformations. The InSAR techniques are being developed since 1990s, and presently used for detecting surface undulations/deformations caused by earthquakes, tectonic activities, volcanic eruptions or hydrogeological fluctuations, as well as monitoring the dynamic phenomenon such as slope movements (e.g., Massonnet *et al.* 1993; Romero *et al.* 2002; Hooper *et al.* 2004, 2007; Chang *et al.* 2004, 2010; Yen *et al.* 2007, 2011; Yhokha *et al.* 2015; Tuan *et al.* 2016). Of the many different InSAR techniques, such as differential InSAR (DInSAR), permanent scatterer InSAR (PSI), small baseline (SB) InSAR, multi-temporal InSAR (MT-InSAR), etc., we have used the PSI, which is reasonably well suited for monitoring even the slowest surface/slope movements (e.g., Colesanti *et al.* 2003, 2006; Cigna *et al.* 2013; Tofani *et al.* 2013; Oliveira *et al.* 2015). As compared to traditional techniques of deciphering and monitoring surface deformations, such as GPS, photogrammetry, laser scanning, etc., the PSI technique has advantages for the following reasons: (a) existing permanent features/elements on the surface, like building, bare ground or rocks, are used as ground motion measurement points, which enable measurements of surface movement without installing any equipment on-site, (b) larger spatial coverage in a particular time frame, (c) ability to measure a variety of observables such as topography, surface deformation etc., of the area in a particular dataset, and (d) time saving and economical. The detailed PSI methodology is described below.

3.1 Persistent Scatterer Interferometry (PSI)

The PSI technique can be defined as a second generation InSAR technique. The characteristic feature and advantage of the PSI is that it uses

multiple SAR images (~ 15 or more) instead of just two images. Moreover, it takes into account the phase information of only those stable back-scatterers that are brighter/stronger than the background scatterers and at the same time maintain the 'coherence' over a sequence of interferograms (figure 4). These stable back-scatterers, called the 'Persistent Scatterers (PS)', can be either man-made or natural features such as buildings, bridges, towers, overhead tanks, rock outcrops, boulders etc., (Hooper *et al.* 2004, 2007; Chang *et al.* 2010; Yen *et al.* 2011). The term 'coherence' is used in interferometry to indicate that the phase information between two back-scatterers is the same and, the 'coherence' of a SAR image is determined by the sum of all phase information of the back-scatterers within a particular resolution pixel. It may be emphasized here that the 'coherence' of the interferograms is lost if the back-scatterers themselves change with respect to each other with time (between satellite passes), such as the vegetated or cultivated areas like the vegetated Himalayan mountains, or, in other words, are not the stable scatterers, like the PS of the PSI techniques (Zebker and Villasenor 1992; Hanssen 2001; Hooper *et al.* 2004, 2007). Therefore, the InSAR techniques other than the PSI generally fail in providing any information on surface deformation in vegetated mountains (e.g., Amelung *et al.* 2000; Hooper *et al.* 2004, 2007) like those of Nainital, and that is the rationale behind applying the PSI technique in the present study.

As of today, there exist many different methods for identifying and isolating the PS pixels in interferograms (e.g., Ferretti *et al.* 2001; Crosetto *et al.* 2003; Adam *et al.* 2005, etc.). In this study, we followed the 'Stanford Method for Persistent Scatterers' (StaMPS) developed by Hooper *et al.* (2004, 2007). This method is considered to be a modified PSI algorithm, in which the phase analysis is done for isolating PS pixel from the surface that enables it to generate more PS points in natural terrains as compared to the other PSI methods (Hooper *et al.* 2004, 2007).

A simplified flow chart of the initial steps of the method is shown in figure 5. Generally, there are two important steps before doing the PSI processing: (i) Raw data focusing (if required), for which ROI-PAC software is used, and (ii) Interferogram generation, for which Doris software is used that has been developed by the Delft University of Technology, Netherlands. One important limiting factor in PSI processing is the accuracy in estimating the

Figure 4. Schematic diagram illustrating difference in SAR phase simulations for distributed scatterer pixel (any InSAR technique other than PSI) and persistent scatterer pixel (PSI technique) (based on Hooper *et al.* 2007).

look angle error, which can be improved by using more number of interferograms, and hence it is advisable to use as many images as possible. Elaborately, in PSI, ‘ N ’ numbers of interferograms are generated with respect to one master image using all the available radar images; the images other than the master image are called the slave images. The phase difference of the x th pixel in the i th interferogram ($\phi_{x,i}$) can be theoretically defined in five terms:

$$\begin{aligned} \phi_{x,i} = & \phi_{\text{def},x,i} + \phi_{\text{atm},x,i} + \phi_{\text{orb},x,i} \\ & + \phi_{\text{topo},x,i} + \phi_{n,x,i} \end{aligned} \quad (1)$$

where ϕ_{def} is phase change due to movement of the pixel in the satellite line-of-sight (LOS) direction, ϕ_{atm} is phase change due to atmospheric retardation, ϕ_{orb} is phase due to orbit inaccuracies, ϕ_{topo} is topographic phase due to error in the DEM and ϕ_n is general noise. The terms ϕ_{def} and ϕ_{orb} in equation (1), are spatially correlated, so that it can be estimated by applying band-pass filters and, ϕ_{atm} atmospheric effect is uncorrelated in time, therefore it is filtered out from the result by high-pass filtering in time and low-pass filtering in space. For rectifying the topographic phase error ϕ_{topo} in our results, we used 3-arcsecond SRTM (Shuttle Radar Topography Mission) DEM data from USGS.

In the present study, 15 C-band radar images of August 2008 to August 2010 from descending

orbit, with track/frame 248/3015, of the ENVISAT satellite have been used (table 1). The image dated 2009/08/07 was used as the master image owing to its smaller perpendicular baselines with the other (slave) images (i.e., the perpendicular distance between two satellites or orbits when the two images were taken). The images used are the single-look complex (SLC) images, which are already corrected for satellite reception errors and contain latitude/longitude positional information.

4. Results

4.1 Mean velocity: Slope movement

The PSI results, obtained in terms of mean LOS velocities (MLV) from several, spatially distributed points (i.e., PS), are shown in figure 6. In this figure, the MLVs, given in mm/year, are shown on an RGB (Red, Green, Blue) scale. The positive and negative values of the MLVs indicate shortening and elongation of the PS points towards the satellite along the LOS, respectively. In our discussion, we considered such shortening and elongation to represent the slope movements representing the resultant of horizontal and vertical components of the movement. As can be seen, the cluster of PS points in the northeastern part of the town is showing prominent movement which is along the slopes of the Sher-ka-Danda ridge (figure 6). The movement at places is as high as ~ 21 mm/year.

Figure 5. Processing flowchart for the present PSI analysis. The radar image was focused by ROI.PAC software and interferometry processes were done by DORIS software, all PS processes were done by StaMPS software developed by [Hooper et al. \(2004\)](#) (modified after [Chang et al. 2010](#); [Yhokha et al. 2015](#)).

Table 1. *Perpendicular baseline (m) and temporal baseline (days) of the image pairs used in the study analysis.*

Image date	Perpendicular baseline (m)	Temporal baseline (days)	Category of image
2008/08/22	170.4	− 350	Slave
2008/09/26	− 91.7	− 315	Slave
2008/10/31	120.3	− 280	Slave
2008/12/05	40.3	− 245	Slave
2009/08/07	—	—	Master
2009/09/11	437.3	35	Slave
2009/10/16	− 196.7	70	Slave
2009/11/20	341	105	Slave
2009/12/25	− 44.2	140	Slave
2010/01/29	303.3	175	Slave
2010/03/05	− 25.3	210	Slave
2010/04/09	284.9	245	Slave
2010/06/18	215.4	315	Slave
2010/07/23	− 103.8	350	Slave
2010/08/27	− 39.7	380	Slave

Figure 6. Map showing spatial distribution of PSI MLV values in Nainital town, during August 2008–August 2010. The values are given in mm/year: blue and red colours indicate elongation and shortening along the LOS, respectively.

Given that the study area is in the mountain, the possibility of topographic error due to side-looking character of the satellite needs to be considered. In case of SAR, the geometry of the satellite orbit and look direction (LOS) with respect to terrain slope could introduce such topography related distortions in the images as the foreshortening or layover. However, the SAR systems are considerably sensitive to movements along slopes facing either east or west and insensitive to movements in either north or south direction. In the present case, the satellite data used are of descending orbit, so the side-looking direction (radar LOS) is westward. Therefore, most reliable results in this study will be obtained from east and west facing slope. As a matter of fact, most of the hill facets in Nainital are only easterly and westerly sloping. Moreover, the most significant slope movements noticed in the area are along the west-facing facets of the Sher-ka-Danda ridge. Admittedly, the results obtained herein can be safely considered reliable.

Based on the spatial distribution of PSI MLV values, we semi-quantitatively delineate the following four distinct creeping zones on western hill slope of the Sher-ka-Danda ridge: (i) H-zone

(high creeping zone), creeping at a rate of > 20 mm/year, (ii) M-zone (moderate creeping zone), creeping at a rate of 15–20 mm/year, (iii) L-zone (low creeping zone), creeping at a rate 5–15 mm/year, and (iv) S-zone (very low creeping zone), creeping at a rate of < 5 mm/year (figure 7).

4.2 Time series deformation: variability in slope movement

The deformation time series revealed a clear spatio-temporal variability in creep rates of H-, M-, and L-zones (figure 8). The fastest creep in all the three zones have been during September 2009–April 2010. Plotting monthly total rainfall of the town against creep rates reveals a roughly positive correlation (figure 8). However, there is no denial to the very fact that the rainfall-induced hydrological fluctuations could affect slope movements even after a time lag, duration of which may depend upon a number of factors including lithology, structure, land cover, thickness of regolith, etc. Nevertheless, there could be many other causes of spatio-temporal variability in the creep, which have not been investigated in the present study but could be taken up in future.

Figure 7. MLV values superimposed on the simplified block diagram of Nainital town. The hill slope is divided into four different creeping zones: H-zone (~ 21 mm/year); M-zone (15–20 mm/year); L-zone (5–15 mm/year); S-zone (< 5 mm/year).

4.3 Hazard risk assessment

The study provides the spatial pattern as well as rate of slope movement during the investigated period, which can be utilized in assessing the risk of mass movement induced disaster in the area. In general, the risk assessment is the process of identifying the hazard, and then evaluating the potential of the damage it could cause.

In the present case, the hazard is slow moving mass movement. Several ground-based studies have shown creep along the Sher-ka-Danda ridge for the past nearly 120 years. The deductions, however, have been based on observations at a few sites only. In contrast, the present results are based on simultaneous observations at several widely distributed sites that are represented as the permanent scatterers in the PSI investigations. Admittedly, the present PSI results have enhanced accuracy in bringing out the spatial and temporal patterns of creep movement. These results revealed spatio-temporal variations in the rate of creep movement during the investigated period (i.e., August 2008–August 2010), facilitating demarcation of H-, M-, L-, and S-zones of high to very low creep rates, respectively. The field evidences such as tilted trees, electricity poles, pillars, building walls,

bended tree trunks, cracks and bulges along the retaining walls, cracks in some of the newly constructed buildings, etc., further confirm active creep along the Sher-ka-Danda ridge.

The maximum creeping rate during the investigated period has been ~ 21 mm/year. Continued creep over longer time period (if not prevented) can result into catastrophic events and it is difficult to determine its exact spatial extent. Thus, there are possibilities that the continued pressure build-up due to unabated creeping could cause devastating landslide along the western slopes of the Sher-ka-Danda ridge in near future. In such an event, the potential risk elements are: the population, buildings and engineering works, economic activities, public service utilities, infrastructure and environmental features in the area. As a matter of deep concern, the Sher-Ka-Danda ridge is the densely populated region of Nainital. Besides private houses, many commercial properties like hotels and shops, government offices, schools, a hospital, recreational areas and network of roads are located on the Sher-ka-Danda ridge. Keeping in view the population, property, business, infrastructure, etc., the M-, L- and S-creeping zone of the Sher-Ka-Danda ridge are at higher risk of slope movement induced disasters, where the

Figure 8. The time series deformation across the H-, M- and L-zones, showing spatio-temporal variations in slope movements. The circles in the left of the figure show the locations (X-axis and Y-axis represent longitude and latitude, respectively) of our PS points, and the graphs in the right show the temporal creep variations. The red colour line in graphs shows the total monthly rainfall in mm (<http://www.imd.gov.in>).

degree of loss with regard to human life could be of the order of hundreds of people (cf. DMMC 2011).

5. Discussion

The main causes of the slope instability in the Sherka-Danda ridge are, highly deformed lithology,

structural discontinuities, close proximity to the active Nainital Fault, unplanned building and road construction on it, and, of course, the subtropical, wet climate of the town. Based on the land use/land cover mapping between the years 2005 and 2010, it has been shown that on an average 35,602 m² of the forested area of Nainital had been encroached every year by various anthropogenic interventions (Rautela *et al.* 2014).

Theodolite monitoring of specially constructed pillars and pegs during the period 1900–1965 revealed that the Sher-ka-Danda ridge experienced continuous creep till 1931, and in short spurts during rains thereafter (Hukku *et al.* 1974). A small portion of the Sher-ka-Danda ridge, corresponding to the area showing maximum movement in our PSI results, showed continuous downward vertical movement during 1902–1919, and sudden subsidence in 1920 and 1933 (Hukku *et al.* 1974). The maximum and minimum displacements in the hill during the period 1910–1979 have been 219.1 and 40 cm, respectively (Sharma 1981). Nevertheless, these deductions were based on temporal monitoring of only a few markers (i.e., pillars and pegs) constructed across the ridge and, thus, could not be considered as accurately revealing the spatio-temporal pattern of creep. On the other hand, our PSI results are based on temporal monitoring of a dense cluster of markers (i.e., permanent scatterers) distributed all through the ridge and, thus, provide highly accurate spatio-temporal pattern of the slope movement. As compared to the creep rates measured during the past century, our PSI results reveal that the central part of the Sher-ka-Danda ridge crept faster during the period of investigation.

Moreover, contrary to episodic nature of the creep during the previous century (Hukku *et al.* 1974), the creep during the period of present investigations has been continuous. There can be many different factors giving rise to this continuous creep movement. However, the positive correlation between the rainfall and creep rate (figure 8) and the rapid increase in unplanned construction of heavy buildings on the Sher-ka-Danda ridge slopes during the period between January 2005 and December 2010 (Census of India 2011) indicate that extreme hydrological events together with impounding weight of building construction could be major causes of making the slopes continuously and rapidly creep. However, this issue needs further detailed and focused investigations in a different research domain that could be taken up in future.

6. Conclusion

The present study demonstrates successful application and utility of PSI technique in identifying and monitoring instable slopes in even the small mountainous settlements like Nainital. The study revealed continuous creep movement along some

parts of the lake facing slope of Sher-ka-Danda ridge during the period August 2008–August 2010. Based on the ranges of PSI MLV, four creeping zone of comparatively rapid to very slow movements have been demarcated as H-, M-, L- and S-zones. The creep rate is higher along the upper reaches of the hill and gradually decreases downhill. The M-, L- and S-creeping zones bear higher risk of damage due to slope movement induced disasters. Besides several geological and anthropogenic causes controlling localization and rate of slope movements, extreme hydrological events and heavy construction load could be the major causes of continuous creep along certain parts of the Sher-ka-Danda. The study calls for recurrent monitoring of slopes in Nainital and other inhabited areas of the Himalaya.

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