Geodetic Analysis of Hill Slope Instability

Hillslope is part of the terrestrial landscape formed from a mosaic of slope types, ranging from steep mountains and cliffs to almost flat plains. Its movement down to slope known as landslide include rock falls, deep failure of slopes, and shallow debris flows is a common natural disaster with severe socio-economic impacts all around the world.[1]–[3] Also, it can be deformed upward and downward due to seasonal freeze-thaw cycles of permafrost[4]–[6]. According to the IPCC report, there is high confidence that changes in precipitation, air temperature, and melting of the permafrost will have an impact on landslide movement in some regions of the world [7]. The gravity force is the main contributor to landslide movement over time in the presence of climate conditions, seismic events, and other processes. The landslide process can be categorized using movement patterns to fall, topple, rotational slide, translational slide, spreads, and flows. The magnitude of displacement rate might be varied from a few millimeters per year to several meters per second [8].

The spatial and temporal pattern of surface slope movement is valuable information to mitigate hazard risk and understand better underlying mechanical processes using spaceborne, airborne, and ground-based sensors. Deformation monitoring techniques and its fusion such as Digital Image Correlation (DIC), Stereo-photogrammetry, LiDAR point-clouds, SAR Interferometry, GNSS(Global Navigation Satellite System) measurements, Electronic distance meters, and total stations surveys are widely used to map hillslope process based on movement pattern and slope displacement rate. Landslide inventories, rapid landslide characterization, and landslide forecast models rely on data derived from remotely sensed observation and statistical or process-based models [9], [10].

InSAR is currently a very powerful and cost-effective tool to map the slope surface movement in sub-centimeter precision over a large area with relatively good Spatio-temporal coverage after applying various geometric and atmospheric corrections.[11]–[13]. The accuracy and precision of InSAR deformation depend on spatial and temporal decorrelation of the SAR signal, the atmospheric delay, and the phase unwrapping error. SAR signal decorrelate according to the temporal and perpendicular baseline of acquisition. One limitation of InSAR observation is the interferometric phase is measured in the slant range direction therefore, a combination of several different geometries is essential to produce different vector components of deformation in space or plane. The vertical and the east-west direction can be extracted from a combination of ascending and descending tracks data, however, the north-south component is difficult to achieve because insensitivity to observe at along-track direction [14].To acquire the north-south component, the inverse model requires at least, one independent measurement retrieved from another geodetic data source such as InSAR from another satellite, GNSS, or ground-based radar observation. The assumption of prior characteristics of deformation geometry is useful to construct a 3D deformation field for instance in the slope movement case, the motion in the direction towards the aspect of downslope might be reasonable. [1], [15]

InSAR phase can be contaminated by atmospheric conditions either through tropospheric or ionospheric effects. Tropospheric phase delay might result from the refractivity index of the troposphere being slightly above that of free space separated into wet and dry components, and even can consist up to 15–20 cm in deformation signal [16] There are several methods to estimate and mitigate tropospheric phase referred as the atmospheric phase screen (APS) by auxiliary information and combination of observation based on weather models [17], [18] GPS measurements [19] and multi-spectral observations MERIS and MODIS images [20]. InSAR Phase is sensitive to ionospheric total electron content (TEC). Blurring in range and azimuth directions in amplitude make coregistration difficult and it decreases the coherence level because of Faraday rotation would result in phase delay in InSAR measurements [21]

InSAR time series correction can be grouped into permanent scatter (PS) methods and distributed scatter methods (DS)[22], [23]. The permanent scatter method relies on the phase stable point scatter which is more suited to the urban area⁠ however distributed scatter methods work better for areas influenced by the decorrelation area and the condition is not limited by phase stability. The DS methods are divided into two subdomains. The first one is known as the small temporal and spatial baseline (SBAS) category [24] introduced based on solving linear systems by minimizing L1-norm using the least square estimator for networks of unwrapped interferograms [25]. In the case of a not fully connected network, the solution of the system can be achieved by regularization or singular value decomposition[26]. The second category of distributed scatter is derived by full exploitation of all possible interferograms and conditions of network redundancy.[27]–[29]

In our study, we aim to apply InSAR and other geodetic techniques to map and detect hill slope processes including landslides movement and freeze-thaw cycles of permafrost .we will derive the InSAR deformation field from different InSAR time series approach to compare the method with atmospheric and unwrapping correction. The 3D/2D field of displacements filed using a combination of InSAR ascending and descending tracks and other independent observations will be extracted. The relation between landslide kinematic and climate factors like precipitation and temperature and geological parameters like groundwater level and soil mechanical properties will be assessed. The statistical analysis can be applied to our geodetic and hydrologic observations to find the relation between deformation rates and pore pressure. To calculate landslide volume, the thickness of the moving slope will be estimated using inversion of surface velocity[1], [11], [30]–[32]. We will model the kinematic and dynamic behavior of the hill slope movement in the presence of rainfall and groundwater level changes.

Research Question

1. To what extend we can detect and monitor hill slope deformation using InSAR processing techniques in the spatial and temporal domain?
2. To what extend different InSAR stack correction methods including InSAR time series techniques, atmospheric correction using different ionospheric and tropospheric approaches and unwrapping techniques can enhance deformation measurement in the hill slope area?
3. To what extend a combination of different InSAR tracks, other geodetic techniques and photogrammetric observation can result in reasonable 3D/2D deformation fields?
4. What is the key driving force of the hill slope area are triggering and moving it in presence of climate, hydrological, and seismic factors?

[1] X. Hu and R. Bürgmann, “Rheology of a Debris Slide From the Joint Analysis of UAVSAR and LiDAR Data,” *Geophys. Res. Lett.*, vol. 47, no. 8, pp. 1–9, 2020, doi: 10.1029/2020GL087452.

[2] A. G. Singleton, “Analysing Landslides in the Threee Gorges Region (China) Using Frequently Acquired SAR Images,” 2014.

[3] R. van Beek, E. Cammeraat, V. Andreu, S. B. Mickovski, and L. Dorren, “HILLSLOPE PROCESSES : MASS WASTING , SLOPE STABILITY AND EROSION The role of man in triggering slope processes is considerable,” *Slope Stab. Eros. Control Ecotechnological Solut.*, pp. 17–64, 2008.

[4] L. Liu, T. Zhang, and J. Wahr, “InSAR measurements of surface deformation over permafrost on the North Slope of Alaska,” *J. Geophys. Res. Earth Surf.*, vol. 115, no. 3, pp. 1–14, 2010, doi: 10.1029/2009JF001547.

[5] S. Daout, M. P. Doin, G. Peltzer, A. Socquet, and C. Lasserre, “Large-scale InSAR monitoring of permafrost freeze-thaw cycles on the Tibetan Plateau,” *Geophys. Res. Lett.*, vol. 44, no. 2, pp. 901–909, 2017, doi: 10.1002/2016GL070781.

[6] X. Hu, Z. Lu, T. C. Pierson, R. Kramer, and D. L. George, “Combining InSAR and GPS to Determine Transient Movement and Thickness of a Seasonally Active Low-Gradient Translational Landslide,” *Geophys. Res. Lett.*, vol. 45, no. 3, pp. 1453–1462, 2018, doi: 10.1002/2017GL076623.

[7] 2012. IPCC and and P. M. M. eds. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, “IPCC, 2012,” *Cambridge University Press, Cambridge, UK, and New York, NY,*. 2012.

[8] D. . J. . Cruden , D . M ., Varnes, “Landslide Types and Processes , Special Report , Transportation Research Board , National Academy of Sciences , 247 : 36-75,” no. January 1996, pp. 36–75, 2016.

[9] A. Stumpf, J. P. Malet, and C. Delacourt, “Correlation of satellite image time-series for the detection and monitoring of slow-moving landslides,” *Remote Sens. Environ.*, vol. 189, no. February, pp. 40–55, 2017, doi: 10.1016/j.rse.2016.11.007.

[10] A. Stumpf, “PhD Thesis presented by Landslide recognition and monitoring with remotely sensed data from passive optical sensors,” 2013.

[11] J. Biggs and T. J. Wright, “How satellite InSAR has grown from opportunistic science to routine monitoring over the last decade,” *Nat. Commun.*, vol. 11, no. 1, pp. 10–13, 2020, doi: 10.1038/s41467-020-17587-6.

[12] D. Massonnet *et al.*, “The displacement field of the Landers earthquake mapped by radar interferometry,” *Nature*, vol. 364, no. 6433, pp. 138–142, 1993.

[13] R. Bamler and P. Hartl, “Synthetic aperture radar interferometry Synthetic aperture radar interferometry,” *Inverse Probl.*, vol. 14, no. 4, p. 55, 1998, doi: 10.1088/0266-5611/14/4/001.

[14] A. Ferretti, A. Rucci, A. Tamburini, S. Del Conte, and S. Cespa, “Advanced InSAR for reservoir geomechanical analysis,” in *EAGE Workshop on Geomechanics in the Oil and Gas Industry*, 2014, doi: 10.3997/2214-4609.20140459.

[15] N. H. Isya, W. Niemeier, and M. Gerke, “3D ESTIMATION of SLOW GROUND MOTION USING INSAR and the SLOPE ASPECT ASSUMPTION, A CASE STUDY: The PUNCAK PASS LANDSLIDE, Indonesia,” *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. 4, no. 2/W5, pp. 623–630, 2019, doi: 10.5194/isprs-annals-IV-2-W5-623-2019.

[16] D. P. S. Bekaert, R. J. Walters, T. J. Wright, a J. Hooper, and D. J. Parker, “Remote Sensing of Environment Statistical comparison of InSAR tropospheric correction techniques,” *Remote Sens. Environ.*, vol. 170, pp. 40–47, 2015, doi: 10.1016/j.rse.2015.08.035.

[17] O. Cavalié *et al.*, “Measurement of interseismic strain across the Haiyuan fault (Gansu, China), by InSAR,” *Earth Planet. Sci. Lett.*, vol. 275, no. 3–4, pp. 246–257, 2008, doi: 10.1016/j.epsl.2008.07.057.

[18] R. Jolivet, R. Grandin, C. Lasserre, M. P. Doin, and G. Peltzer, “Systematic InSAR tropospheric phase delay corrections from global meteorological reanalysis data,” *Geophys. Res. Lett.*, vol. 38, no. 17, pp. 1–6, 2011, doi: 10.1029/2011GL048757.

[19] G. Wadge *et al.*, “Atmospheric models, GPS and InSAR measurements of the tropospheric water vapour field over Mount Etna,” *Geophys. Res. Lett.*, vol. 29, no. 19, p. 11, 2002.

[20] Z. Li, J. P. Muller, P. Cross, and E. J. Fielding, “Interferometric synthetic aperture radar (InSAR) atmospheric correction: GPS, Moderate Resolution Imaging Spectroradiometer (MODIS), and InSAR integration,” *J. Geophys. Res. Solid Earth*, 2005, doi: 10.1029/2004JB003446.

[21] U. Wegmüller, C. Werner, T. Strozzi, and A. Wiesmann, “Ionospheric electron concentration effects on SAR and INSAR,” in *International Geoscience and Remote Sensing Symposium (IGARSS)*, 2006, pp. 3731–3734, doi: 10.1109/IGARSS.2006.956.

[22] A. Ferretti, C. Prati, and F. Rocca, “Permanent scatterers in SAR interferometry,” *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 1, pp. 8–20, 2001, doi: 10.1109/36.898661.

[23] A. Hooper, H. Zebker, P. Segall, and B. Kampes, “A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers,” *Geophys. Res. Lett.*, vol. 31, no. 23, pp. 1–5, 2004, doi: 10.1029/2004GL021737.

[24] P. Berardino, G. Fornaro, R. Lanari, and E. Sansosti, “A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms,” *IEEE Trans. Geosci. Remote Sens.*, vol. 40, no. 11, pp. 2375–2383, Nov. 2002, doi: 10.1109/TGRS.2002.803792.

[25] T. R. Lauknes, H. A. Zebker, and Y. Larsen, “InSAR deformation time series using an L1-norm small-baseline approach,” *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 1 PART 2, pp. 536–546, 2011, doi: 10.1109/TGRS.2010.2051951.

[26] P. López-quiroz, M. Doin, F. Tupin, P. Briole, and J. Nicolas, “Time series analysis of Mexico City subsidence constrained by radar interferometry,” *J. Appl. Geophys.*, vol. 69, no. 1, pp. 1–15, 2009, doi: 10.1016/j.jappgeo.2009.02.006.

[27] A. M. Guarnieri and S. Tebaldini, “Hybrid Cramér – Rao Bounds for Crustal Displacement Field Estimators in SAR Interferometry,” vol. 14, no. 12, pp. 1012–1015, 2007.

[28] A. M. Guarnieri and S. Tebaldini, “On the Exploitation of Target Statistics for SAR Interferometry Applications,” vol. 46, no. 11, pp. 3436–3443, 2008.

[29] A. Ferretti, A. Fumagalli, F. Novali, C. Prati, F. Rocca, and A. Rucci, “A new algorithm for processing interferometric data-stacks: SqueeSAR,” *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 9, pp. 3460–3470, 2011, doi: 10.1109/TGRS.2011.2124465.

[30] X. Hu, R. Bürgmann, Z. Lu, A. L. Handwerger, T. Wang, and R. Miao, “Mobility, Thickness, and Hydraulic Diffusivity of the Slow-Moving Monroe Landslide in California Revealed by L-Band Satellite Radar Interferometry,” *J. Geophys. Res. Solid Earth*, vol. 124, no. 7, pp. 7504–7518, 2019, doi: 10.1029/2019JB017560.

[31] X. Hu, R. Bürgmann, W. H. Schulz, and E. J. Fielding, “Four-dimensional surface motions of the Slumgullion landslide and quantification of hydrometeorological forcing,” *Nat. Commun.*, vol. 11, no. 1, pp. 1–9, 2020, doi: 10.1038/s41467-020-16617-7.

[32] Y. Xu, J. Kim, D. L. George, and Z. Lu, “Characterizing seasonally rainfall-driven movement of a translational landslide using SAR imagery and SMAP soil moisture,” *Remote Sens.*, vol. 11, no. 20, 2019, doi: 10.3390/rs11202347.