Role of Emerging Aerospace-Based Technology, Geophysical Investigation and Numerical Simulation in Landslide Hazard Mapping, Modelling and Mitigation

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Abstract

Some innovative methods were demonstrated for the first time to acquire data related to landslides and attempt modelling. The TLS of Riegl VZ 400 make was used for acquiring dense point cloud with an average spacing of 1cm with an accuracy of 5mm. DTM, hill shade, aspect and slope map of the landslide were generated, which were found very useful for detailed landslide mapping, modelling and analysis. UAV based ultrahigh-resolution mapping has independently emerged as a complementary technique to satellite/aerial remote sensing in steep terrain and under heavy cloudy conditions. At Baliyanala landslide in Nainital, the technology was demonstrated to assist the state government in acquiring authentic information on the extent of a landslide in 3-D along with high-resolution DEM and surface cover. Geophysical investigations can help to determine the slip surface and other sub-surface details alternatively which can only be obtained by expensive and time-consuming drilling. One such scarp of 600m length was detected at Kunjethi (Kalimath) village (Uttarakhand) on satellite images during routine analysis to confirm the presence of landslide scarp, its dimension, depth and geometry of the slip surface using resistivity and GPR technology. The numerical simulation model has also been employed that predicts run out in three dimensions and provide velocity, momentum, height and pressure at Kaliyasaur landslide. These emerging technologies cater to high-resolution terrain attributes essential for landslide modelling, designing remedial measures, to

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evacuate people and also help to simulate and understand the actual cause, process and mechanism of landslides.

Key Words: TLS, Baliyanala, UAV, simulation, GPR, Kaliyasaur.

Introduction

Landslide is one of the major geological hazards in the Himalayan states of India. It also contributes to natural disasters in the mountainous region around the globe because of causative and triggering factors like heavy rainstorms, cloudbursts, glacial lake outburst (GLOF), earthquakes, geo-engineering setting, anthropogenic activities, etc. Landslide occurrences wreck havoc on life, property and livelihood of this mountainous area, thriving mainly on pilgrimage, tourism and agriculture (Anbalagan et al., 2015; Anbalagan, 1992; Champati Ray and Chattoraj, 2014; Gupta et al., 1993; Kumar et al., 2012; Onagh et al., 2012; Sarkar et al., 1995, 2006; Sundriyal et al., 2007). Being situated at a higher elevation, rough hilly landscape, scanty cultivated land, strong monsoonal effect and less industrial growth restricting economic progress, repeated landslide events keep human life and property at stake (Champati Ray et al., 2013a, b; Champati Ray et al., 2015; Paul and Bist, 1993). However, there have been efforts to minimise the loss by characterisation, mapping, monitoring, modelling and mitigations by advance technologies including the space-based ones.

Since the beginning of this century, LiDAR are being used extensively for generating digital surfaces model and digital terrain models. Terrestrial laser scanners are being used for mapping and monitoring of landslides as they provide unprecedented levels of details at sites having high slopes in terms of resolution and accuracy. Recent trends in high-resolution mapping employ UAVs for stereo image acquisition as it has advantages such as operational flexibility, rapid deployment, flight repeatability, low operational costs, and fewer weather-related flying limitations over traditional platforms. Mostly used UAVs in geospatial mapping are multi-rotor and fixed drone. Geophysical investigations for landslide characterisation is a relatively new tool that can determine the slip surface and other sub-surface details, which can otherwise be obtained by expensive and time-consuming drilling. During Kedarnath tragedy in 2013 numerous landslides occurred and many hill slopes and steep river banks developed fractures and fissures indicative of landslides. ERT methods are based on the variation of electrical resistivity of the subsurface material (Kannaujiya et al., 2019). The method is based on single-channel 4-electrode arrays, where 2 electrodes are used for current injection and 2 for voltage measurements. The surveys were carried out by a Lippmann 4 point light

10 W IP earth resistivity meter, coupled with a multi-electrode system (40 electrodes), using pole–dipole and dipole-dipole configurations for obtaining different investigation depth. An electronic switching unit automatically selects the four electrodes required for each measurement. Data acquisition was done in this study using Geotest software (© Dr. Rauen) with an electrode spacing of 5 m for an array length of 200 m. Loke and Barker (1996) and Binley and Kemna (2005) stressed upon that 'inverse problem' needs to be solved which means a given a set of measurements (data), the distribution of electrical properties (model) is sought to check the degree of acceptability of observations. Ground-penetrating radar (GPR) is a proven technique capable of providing highest possible resolution (using 100 MHz antennae) suitable for shallow subsurface exploration (Asprion and Aigner, 1999; Reiss et al., 2003). Debris flow modelling is an active area of research and the underlying principle can be applied to a variety of processes including snow avalanche, debris flows, landslides, mudflows and even rock falls and has therefore found a significant role in disaster management. Although well tested empirical methods are available to determine the dynamic characteristic of a flow, numerical simulation techniques are now applied to predict flow paths and characterise the entrainment process. The present study aims to fill this knowledge gap by focusing integrated EO based technology, geophysical tools and numerical simulations for characterisation of major landslides/debris flow movements in the Garhwal Himalaya.

Material and Methods

In the present paper, an integrated approach was adopted to acquire data related to landslides and attempt modelling that can be used for designing remedial measure and save lives and property during disasters.The study locations include Kaliyasaur/ Sheerobagarh (TLS and numerical simulation), Nainital (UAV) and Kalimath (Geophysical methods) of Garhwal and Kumaun Himalaya.

The present case study has been taken up at Kaliyasaur/Sheerobagarh landslide, near Srinagar, Garhwal, which has been troubling the traffic towards Badrinath. For mapping this landslide Riegl VZ 400 was used for acquiring dense point cloud with an average space of 1cm with an accuracy of 5mm. Data was acquired from the landslide and was coregistered using common tie points. Co-registered dense point data was manually edited to remove point corresponding to vegetation. Township of Nainital has a historical record of landslides. Efforts have been made in the past to mitigate the same; however, with a growing population, the efforts have been reduced due to overlooking of age-old mitigation measures, unplanned and rapid developmental initiatives on the vulnerable slopes. Off late, the Baliyanala landslide in Nainital is also creating the problem. The rocks along the Balianala belong to Infra Krol and Krol Formations. The rocks are highly sheared and faulted because of the presence of number of shear planes and normal faults. Seepage is observed at the contact of the rocks. The rocky outcrops are highly weathered. The bedding plane generally dips at gentle to steep angles (10°-45°) towards north, northwest and southwest. The entire slope in the landslide zone in the upper part is mainly made up of weathered dolomitic limestone and lower part of the slope is made up of carbonaceous slate. The debris material/ slope wash material comprises angular to subangular class mainly of dolomitic limestone, limestone, calcareous slates of size varying from few mm to boulder size embedded in silty clay matrix (Routela and Khanduri, 2011; DMMC, 2018). The slide was mapped and monitored using UAV technology, with onboard visual/multispectral sensors. Since multi-rotor drones are more flexible than fixed-wing drone, in this case, study DJI inspires 2 quadroter are used which was mounted with 20 MP camera zenmuse x4s camera. For mapping the landslide and its surrounding built-up area, mission planning was done to ensure that the ground sampling distance is less than 5 cm and has at least 80 per cent forward overlap and 60 per cent side overlap. Total 533 overlapping photographs were acquired with an average GSD of 1.2 cm covering a total area of 12.8 acres. Along with these data, 6 ground control points are acquired using Differential GPS in real-time mode with an accuracy of 1cm after post-processing. Photographs from all missions are processed using commercial software a gisoft and pix4d to generate a dense point cloud.

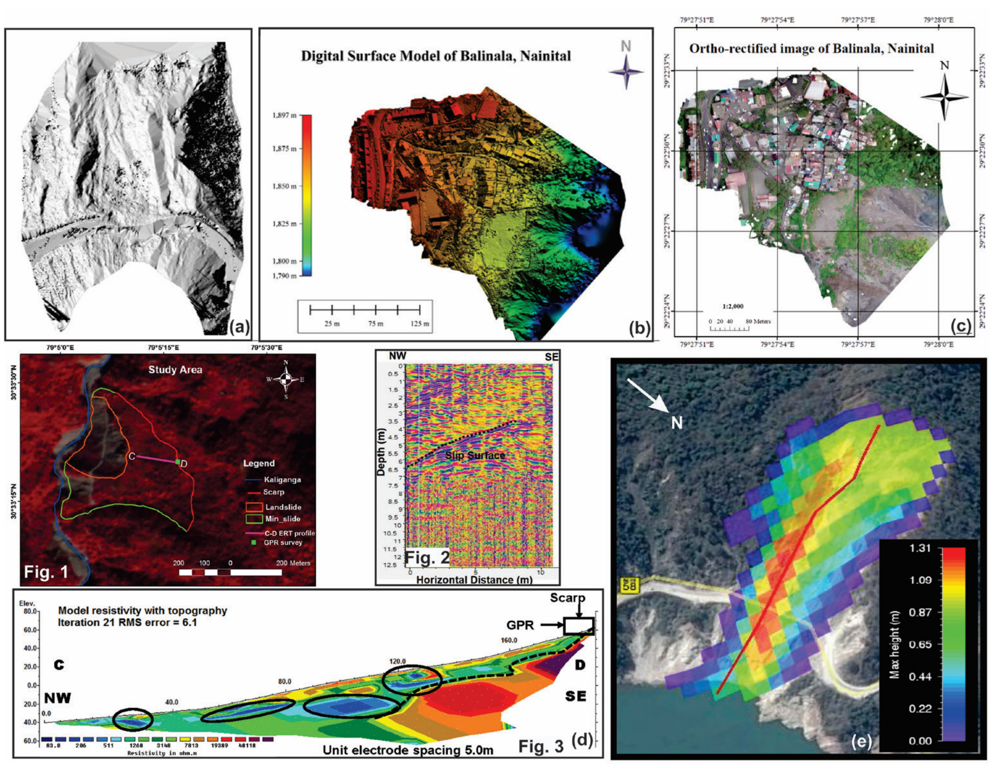
Geophysical technology was employed at Kaliganga river valley, close to Kalimath, situated in Rudraprayag district, covering an area of 5.64 to study a landslide scarp is approximately 685 m long located above the Kunjethi-Kotma road. The lithology of the area comprised mainly of metamorphic rocks and granitic intrusions and situated in Central Crystalline Zone of Himalaya (Valdiya et al., 1999). Two major lithotectonic units namely Munsiari Group (lithologicallycataclastic/mylonitized rocks and granites of Middle Proterozoic) and Vaikrita Group (lithologically medium to high-grade metamorphic rocks and porphyritic granite gneiss) divides the area separated by Vaikrita Thrust (Main Central Thrust—MCT-II) (Valdiya et al., 1999). Geomorphologically, high to moderately dissected hills, sinus second-order rivers adorns the area mostly. The slide is highly rugged at its active portion, at places, with a maximum height of around 1560 m, and rivers flowing at around 1200 m MSL. It is also covered with weathered derivatives of the rocks (described above) and sparse vegetation. Tectonically, it broadly dips towards west and structures like empty sympathetic cracks (terminated laterally at bedrocks) parallel to the arcuate source region of landslide are visible on the ground. Along landslide portion, the slope of the topography is 25° to 40° on hillside. Hydrogeologically, the area falls under a discharge zone bounded by spring-fed water shoots on both the sides of the landslide.

Modelling of debris flows is process-based approach in principle and considers avalanches, flows (mud and debris), falls and hence important in disaster management and mitigation (Cruden and Vernes, 1996; Iverson et al., 1997). Particularly, debris flows can be defined as gravity-induced flows comprising of inhomogeneous materials mixed with a liquid phase resulting in a devastating event. With the availability of globally accepted empirical equations employed to characterise kinematics of a flow, there is an increased demand come up with sophisticated mathematical simulations which can be utilised to mimic flow paths and analyse the process of entrainment (Tsai et al., 2011; Quan Luna et al., 2011). This work utilised the RAMMS (Rapid Mass Movements Software) model, presented by WSL Institute of Snow and Avalanche, Switzerland, to model the natural flow of a dislodged geophysical mass in 3-dimension from source (release) to base (deposition). A high-resolution Digital Elevation Model supported by ancillary ground truth data are important inputs to the model, reinforced with various geomechanical parameters. To understand the failure behaviour, Voellmy rheological model has been employed to take care to physically characterise the entrainment of debris material. This gives rise to a physical-based model showing the spatial variation of flow, height, velocity, pressure and momentum along the torrent (Christen et al., 2010; Ayotte and Hunger, 2000; Rickenmann, 2005). The Kaliyasaur/Sheerobagarh landslide was modelled using the numerical simulation technique using space-based cues. The study area mainly comprises of metavolcanic and variants of quartzite rock in pink and white colour with occasional bands of shale. As per regional geological studies, the whole area broadly belongs to Lesser Himalayan divisions (Kumar et al., 2013). The initiation zone lies at top of Kaliyasaur hill at an elevation of 845 m has a slope of approximately 60 to 75 degree. This particular area has been dissected by a number of joints and moreover, a major fault passes through this zone (Bist and Sinha, 1980). The average length of run out from the initiation zone to road cross cut is approximately 215 m and avg. 300 m up to the river. From the field observation, it was clear that the modelled landslide was initiated with a rockfall and then flowed downward in the form of the torrent. Bulk density of 2450 kg/m^3 was used quartzite and phyllites and their weathered derivatives which are highly shattered, fragmented and thinly jointed with any shear zones.

Results

One of the emerging technologies is LiDAR-based Terrestrial laser scanning which is used for generating digital terrain models (DTM) that provide high-resolution terrain attributes essential for landslide modelling. Realising its tremendous application potential, a case study was taken up at very critical Kaliyasaur landslide, on Rishikesh-Badrinath highway. Terrestrial Laser Scan resulted in the generation of the digital terrain model, hillshade, aspect and slope map of the landslide (Fig. 1a). As for the UAV drone derived outputs, source area of the landslide at Baliyanala, Nainital was modelled. A UAV (DJI inspire 2 quadroter)was used with 20 MP camera (Zenmuse x4s) to map the landslide and its surrounding built-up area. In total 533 overlapping photographs were acquired with average GSD of 1.2 cm covering an area of 12.8 acres. DSM of 6 cm was generated with a horizontal and vertical accuracy of 6 cm and 14 cm respectively. Ortho-rectified mosaic of the area was generated at a resolution of 1.2cm. Slope map and contour maps at 1 m contour spacing could also be generated (Fig. 1b-c).

Fig. 1 (a) Hillshed of Kaliyasaur landslide by TLS; (b-c) UAV derived DTM and ortho-rectified image of Baliyanala landslide; (d) GPR radargram and resistivity of the subsurface in Kunjethi landslide; (e) simulated debris height of Kaliyasaur landslide.



In case of resistivity surveys at Kalimath, data would be in the form of transfer resistances or apparent resistivities, whilst in case of IP survey; it would be in the form of apparent chargeability or transfer impedance. The models will be parameterised in terms of resistivity or conductivity and intrinsic chargeability or complex resistivity, respectively. The GPR profiles were obtained with 100 MHz shielded antennas and GRED HD viewer software. A transmitter antenna radiates very short pulses into the subsurface. The pulses are reflected back to a receiver antenna at the surface at boundaries with dielectric contrasts. A series of scans are collected as the antenna, moves along a survey line, typically in constant offset method. Fig. 1d shows inverted profiles with topographic correction, which was obtained in a direction parallel to the longitudinal axis of the landslide. The most striking feature of C–D profile is the sharp lateral discontinuities across which the resistivity values change drastically in the vertical direction. The sharp discontinuity in Fig. 3 is interpreted as the possible slip surface or failure plane that separates the landslide overburden mass/slide materials from the stable bedrock/ underlying mass. GPR profile was acquired with 100 MHz antenna across the developed scarp along the south-eastern end of C-D profile (Fig. 1d). The steeply dipping reflector was clearly identified in GPR radar gram corresponding to the slip surface identified in the ERT profile (Fig.1d).

In the Kaliyasaur/Seerobagarharea, the total release volume was 24358m^3. Maximum height value was recorded to be ~2m (±0.35m) near-road cross-cut (Fig. 1e). According to the field information and satellite images, it is considered to be quite a good match. A gradual change in the topographic slope was observed from the source area till its deposition on the inner bend of the river. Height at the base of deposition becomes 2.5 m (±0.3m). The velocity of the flow changes from 4.85 m/s (±0.25m/s) at the road cross cut to 8.75 m/s (±0.3 m/s) at the base (near the river) owing to increase in slope from the road to the river. The longitudinal profile of the whole run-out zone indicates that increase the height and the velocity of the flow happened in a simultaneous and gradual way. The maximum value pixels of velocity and height are centrally located, albeit. However, intriguingly, the variation of height and velocity in tandem is not revealed by pressure and momentum. Momentum shows a typical maximum range in the middle of the flow with a maximum value located very near to the road crosscut. This, perhaps, is primarily responsible for continuous damage leading to the short life span of the remedial measures provided at the road crosscut. Highest-pressure pixels, however, is restricted only near the source of the flow and the base. The model result also depicts an asymmetric arrangement of maximum values for momentum and pressure parameters. The outputs of such simulation of natural events provide information on run out distance, thickness of debris, momentum and velocity of flow that can be used to evacuate people and design remedial measures and also help to simulate and understand the actual cause, process and mechanism of landslides.

Discussion

With the TLS-derived outputs, 3-D modelling can be carried out at user-defined temporal resolution, thus providing opportunities for temporal analysis which is crucial for monitoring landslides This usually starts as small scale deformation finally lead to large scale displacement of huge masses ranging up to few million cubic meters. UAV based ultra-high resolution mapping has emerged as a complementary technique to satellite/aerial remote sensing in steep terrain and under heavy cloudy conditions. UAVs can be operated in a short time window in any terrain condition, thus providing timely information on very dynamic phenomena like landslides and river blockades that can breach and cause flooding. Therefore, the study area was taken up at Baliyanala landslide in Nainital to demonstrate the technology and assist the state government in acquiring authentic information on the extent of a landslide in 3-D along with high-resolution DEM and surface cover.

Geophysical investigations for landslide characterisation is a relatively new tool that can determine the slip surface and other sub-surface details, alternatively which can only be obtained by expensive and time-consuming drilling. During Kedarnath tragedy in 2013 numerous landslides occurred and many hill slopes and steep river banks developed fractures and fissures indicative of landslides. One such scarp of 600m length was detected at Kunjethi (Kalimath) village (Uttarakhand) on satellite images during routine analysis. As the primary aim of this study was to confirm the presence of landslide scarp, its dimension as observed on satellite images were considered. To determine the depth and geometry of the slip surface of the slowly moving landslide, a combination of electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) were employed. Using 2-D profiles (ERT and GPR), slip surface or failure plane that separates the landslide overburden mass/slide materials from the stable bedrock/underlying mass could be detected.

On June 15-17, 2013, extreme precipitation hovered in Garhwal Himalaya that led to glacial lake outburst flooding accompanying with it, landslides and flash flood events eventually leading to huge toll on life and property (Champati ray et al., 2015; Chattoraj et al., 2018). During its routine analysis satellites preserved images of fractures and fissures that developed along hill slopes and steep river banks, indicating landslides and thus one such scarp was observed at Kunjethi (Kalimath) village. Therefore a highly cost-effective and fast non-invasive geophysical techniques, electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) are employed to characterise the landslide and get subsurface information. Characteristics extraction of this particular landslide scarp (its dimension; observed on satellite images and determine depth and geometry of the slip surface) as well as confirming its presence using ERT and GPR is a major objective of this study (Kannaujiya et al., 2019). The main emphasis of the work is on early detection of a landslide by analysing remotely-sensed satellite data products and geophysical investigations ERT and GPR for subsurface characterisation and detection of the slip surface. The geophysical survey such as ERT and GPR has enabled subsurface characterisation and helped to identify the slip surface which shows good correlation with the weak zone where the landslides scarp has formed. ERT section and GPR radargram profile were used to determine the approximate depth to slip surface, which is inferred around 15-19 m. Integration of satellite remote sensing, geophysical studies and field observations have been used to demarcate the maximum possible slide zone. This study reiterates earth observation tools in integration with faster, non-invasive and cost-effective geophysical techniques which can establish the slip surface, providing essential information required for landslide hazard mitigation measures.

Numerical simulation, adopted in this work, provides four vital physical outputs viz. velocity, height, pressure and momentum of debris flow (Chattoraj et al., 2018). Longitudinal profiling of run-out and point-data collection of a specific location are also permitted. Debris flow height is of major concern due to the fact that the financial costs of clearing huge debris can be very high and debris of large quantity cut off the road and ultimately disrupts the life-line of these hilly areas. Therefore velocity and momentum are very important to specify the type and nature of any remedial structures which can withstand the initial thrust of the flow and arrest further movement of flow and reduce damage. Variations of vital physical parameters of simulations are discussed. However, RAMMS derived models neither consider side-channel contribution or assimilation of mass due to en-route erosion of the flow which presumably will increase the volume. The simulated height and momentum thus are to be considered as a lower limit of the parameters while the flow may have been more powerful in reality. Amongst RAMMS model outputs, momentum is not absolute as it simply considers momentum as a product of flow height and velocity. Thus the unit is m^2/s. To get real momentum in (kg*m/s), this value is multiplied by the density of debris and area under consideration.

Conclusion

Landslide hazard/susceptibility mapping aided by EO based techniques and analysis of geoengineering aspects has helped damage assessment by and large. Hence there is a requirement of advanced space/air-borne technologies to be employed for better mapping, characterisation and monitoring of landslides. The TLS which were found very useful for detailed landslide mapping, modelling and analysis of Kaliyasaur/ Sheerobagarhlandslide. The ultra-high-resolution UAV-based spatial database is of immense value for designing remedial measures and evacuating people from expanding the crown part of the landslide. A major emphasis of the work was to understand the initiation of landslide process by geophysical investigations (ERT and GPR) for subsurface characterisation of landslide mass. Most of the landslides in Uttarakhand have a major debris flow component that travels some distance causing enormous damage en-route. Comprehensive assessment of landslide hazard requires process-based modelling using simulation methods Analysis and simulation of major landslides/debris flow events (post-facto and predictive) in the Garhwal Himalaya lead to the derivation of the important physical flow parameters for most vulnerable locations based TLS or UAV based mapping provided high/ultra-high-resolution terrain attributes. Future potential debris flows at nearby vulnerable locations and change detection can be modelled for similar geology and topography. Of late, LiDAR/TLS, UAV based technology, complemented by numerical simulation and geophysical validation entail for better understanding of the landslide to help mitigation, decision making and thus becomes crucial to all stakeholders.

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