INTERNATIONAL WORKSHOP ON ASSESSMENT AND MITIGATION OF LANDSLIDES IN THE HIMALAYA

March 13-14, 2020

ABSTRACT VOLUME

Organised by

वाडिया हिमालय भू-विज्ञान संस्थान
1968
WIHG

WADIA INSTITUTE OF HIMALAYAN GEOLOGY
DEHRADUN 248001, INDIA

International Workshop on Assessment and Mitigation of Landslides in the Himalaya
March 13-14, 2020

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ABSTRACT VOLUME

International Workshop on Assessment and Mitigation of Landslides in the Himalaya

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WADIA INSTITUTE OF HIMALAYAN GEOLOGY
(An Autonomous Institute of Department of Science & Technology, Government of India)
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सत्यमेव जयते
प्रो. आशुतोष शर्मा
Prof. Ashutosh Sharma

स्वच्छ भारत
एक कदम स्वच्छता की ओर

सचिव
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विज्ञान और प्रौद्योगिकी विभाग
Secretary
Government of India
Ministry of Science and Technology
Department of Science and Technology

6th March, 2020

MESSAGE

I am happy to know that Wadia Institute of Himalayan Geology, Dehradun is organizing an International Workshop on the "Assessment and Mitigation of Landslides in the Himalaya" at its premises during March 13-14, 2020.

Landslide is one of the most common geological hazards in the Himalaya and adjoining hilly regions. Infrastructures worth of billions of rupees are lost and hundreds of people are killed every year due to this geohazard. The landslide also causes the environmental degradation that has been rising day-by-day due to anthropogenic influences. I am confident that this workshop will provide great opportunities to the young Earth Scientists for interaction with the eminent academicians and professionals who will be deliberating on this occasion. I am sure that participation in the workshop would be memorable and fruitful in understanding the issues related to geo-hazards and providing precautionary measures in mitigating their impacts.

I wish the Workshop a resounding success.

(Ashutosh Sharma)

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सत्यमेव जयते

डॉ. एम. राजीवन
DR. M. RAJEEVAN

सचिव
भारत सरकार
पृथ्वी विज्ञान मंत्रालय
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SECRETARY
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
PRITHVI BHAVAN, LODHI ROAD, NEW DELHI-110003

MESSAGE

It gives me immense pleasure to learn that an International Workshop on the "Assessment and Mitigation of Landslides in the Himalaya" is being held at the Wadia Institute of Himalayan Geology, Dehradun during 13 - 14 of March, 2020.

Landslides and earthquakes - the two major geological hazards - are ubiquitous in the Himalayan terrain, and are difficult to comprehend their spatio-temporal distribution in the complex scenario. In many developed countries, landslides are being tamed to reduce their impacts by installing early warning system and implementing land-use policy. Installing early warning system on each critical slope for a vast country like India is a real challenge. This two-day workshop will provide a platform to understand several issues related to landslides, and mitigate the losses caused by landslides in the slope areas of the Himalayan terrain.

I congratulate the organizers and wish the International Workshop all success.

(M. Rajeevan)

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33, General Mahadeo Singh Road, Dehradun-248001

Prof. Ashok Sahni
GB (WIHG), Chairman

MESSAGE

It is heartening to note that the International Workshop on "Assessment and Mitigation of Landslides in the Himalaya", is being organized by the Wadia Institute of Himalayan Geology, Dehradun during 13-14 March 2020. This effort by the Institute will lead to greater awareness amongst all those who are affected and will provide the necessary tools to overcome this very common but serious hazard. The Workshop is therefore very pertinent and timely.

I am confident that the deliberations by the geoscientists & engineers attending this workshop will ignite and inspire the young minds for greater benefit to the society. The presentations, networking and interaction of young researchers/students with the experienced/senior researchers will definitely yield excellent results in the areas of landslide hazard mitigation.

I wish the Workshop a grand success.

(Ashok Sahni)
Lucknow
March 2nd, 2020

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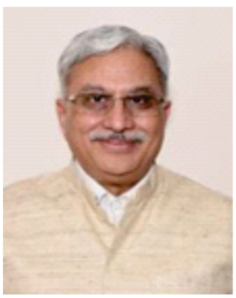
Dr Shailesh Nayak
RAC (WIHG), Chairman

MESSAGE



I am very delighted to see that an International Workshop on the "Assessment and Mitigation of Landslides in the Himalaya" is being held at the Wadia Institute of Himalayan Geology, Dehradun during March 13-14, 2020.

As we all know that landslides, rockfalls, earthquakes, avalanches, floods, cloudbursts etc. often take place in the Himalaya and adjacent terrains. The frequency of these phenomena is on the rising trend, and thus it is essential to assess the potential of these hazardous phenomena with a view to reduce their impacts. I am certain that the deliberations in this dedicated workshop is likely to enrich our knowledge on physical processes that are responsible for the occurrences of natural hazards and suggesting remedial measures.

I congratulate to all the delegates and wish the Workshop all success.

(Shailesh Nayak)

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33, General Mahadeo Singh Road, Dehradun-248001

Dr. Kalachand Sain
Director

2nd March, 2020

MESSAGE

It is indeed an honor to extend warm welcome to all esteem dignitaries, delegates, speakers, invitees to the International Workshop on "Assessment and mitigation of Landslides in the Himalaya", which is being organized at the WIHG, Dehradun during March 13-14, 2020.

A response from around 90 delegates and participants from across India and abroad is a positive stride towards the success of this focused workshop. As the Himalayan terrain has witnessed greater number of landslides in recent times, convening this workshop is indeed a great occasion for celebration. I am optimistic that the two-day deliberations will be immensely useful in comprehending the causes of landslides and plausible mitigation so as to avoid the losses of lives and damages of properties for securing sustainable development and secured living in the Himalaya and adjoining mountains.

As a Chairman of the Organizing Committee I present this abstract volume before the participants as a ready reference, which will be discussed in details by all the participants.

Wishing the workshop a grand success.

(Kalachand Sain)

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33, General Mahadeo Singh Road, Dehradun-248001

Dear Colleagues and Friends,

As a Convener of the Workshop, I wish to extend a warm welcome to the International Workshop on "Assessment and Mitigation of Landslides in the Himalaya" at the Wadia Institute of Himalayan Geology, Dehradun during 13-14 March 2020. It is my pleasure to welcome you to this important event.

Landslide is one of the major geological hazards in the Himalayan terrain and is one of the primary reason of environmental degradation of the region. It poses serious threat to the infrastructure and socio-economic conditions of the people of the region. It is estimated that ~30% of the world's landslides occur in the Himalayan terrain, and the monetary loss incurred in India is ~100 million $ per year. With the ever increasing pressure of development in the form of construction of roads, tunnels, dams, bridges, hydropower projects etc., the losses incurred due to landslides are increasing exponentially. There is thus an immense need to assess the landslide susceptibility and hazards in the pan Himalayan region, as the slope conditions vary regionally along and across the Himalaya. This requires the regional scale assessments of landslide susceptibility and hazard. We also need to build the prevention strategies for mitigating the impact of related hazards. In this context, two-day International Workshop on "Assessment and Mitigation of Landslides in the Himalaya" is being organized at the 'Wadia Institute of Himalayan Geology (WIHG), Dehradun during March 13-14, 2020.

We have received about 80 abstracts from researchers and professional from across India as well as from aboard, including from Norway, Netherland, Switzerland and UK. There shall be about 35 Oral and ~40 Poster presentations. It is proposed to award the First and the Second prizes for the Best Poster presentation.

This two-day deliberations will include invited talks, special talks on the landslides hazards in the Sikkim Himalaya, and the Large scale mapping in the Uttarakhand Himalaya, besides the presentations of contributory papers (oral and poster) on the following themes;

Landslide Hazard, Vulnerability and Risk Assessment
Landslide Mechanism and Modelling
Special session on Landslides in the Sikkim Himalaya
Special session on Large Scale Mapping
Early Warning, Best Practices and Landslide Mitigation

The purpose of this workshop would be sharing scientific knowledge and experiences through case studies and best practices by the experts of different institutes including the ministries, international agencies and landslide researchers. This would add value to the present understanding of different approaches used in landslide studies and policy planning & practices, and enable to prepare a roadmap for addressing risks and vulnerability in the region. It would also help in developing network of institutions and experts around the thematic areas of the workshop.

I thank the workshop committee for extending their valuable time and efforts in organizing the program and all the authors, reviewers, and other contributors for their sparkling efforts and their belief in the excellence of the workshop.

(Vikram Gupta)

Contents

Numerical Study of Stability of Slopes Subjected to Rail Induced Vibration

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The rate of construction of infrastructures is rapidly increasing due to the increase in population and tourism purposes in the Himalayan region. Recently, many railway projects are going on in the Himalayan and north-eastern regions of India. The stability of slopes may decrease due to railway induced vibration. Very few literature is available to study the influence of rail induced vibration on the stability of existing slopes (β = 20° and 30°). Therefore, an attempt is made to access the stability of slopes under rail vibration numerically. In the present study, the three-dimensional finite element method (3D-FEM) is adopted in PLAXIS 3D. Initially, the soil and rail track are considered as a linear elastic material. Further, to consider the soil non-linearity, the Mohr-Coulomb constitutive model is considered. The effect of rail speed, soil properties and slope angle are considered to examine the stability of slopes. The stability of slopes under railway induced vibration is reported in terms of displacement. To simulate the dynamic stability of slopes, free field boundary condition has been assumed with a proper material damping. The ground response analysis (GRA) is conducted to check the proper wave propagation through the soil elements. From the obtained result, it is observed that the deformation of slopes increases with the increase of rail speed. However, the soil material properties have a significant role in the stability of slopes under rail vibration. The detailed effect of slope angles, rail speed and soil properties on the deformation of slopes has been analysed.

Socio-Economic Impacts of Rock Slides on Himalayan Region - a case study

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Himalaya is one of the highly prone regions for landslide disasters in the world. State and National Highways along the Himalayan region being unstable and prone to various landslide disasters is of major concern in the region. Unplanned excavation of the slopes has caused instability among the slopes leading to rock and soil failure. The current Research is focused on the studying the Socio and Economic Implications of landslides and its related slope instability and kinematic analysis of rainfall induced rock slide along NH-22 near Dhalli tunnel in Shimla town. Dhalli landslide which occurred along a road cut slope without proper toe support in September, 2017, is a structurally controlled landslide. Kinematic analysis was performed to analyse the type of rock failure in the study area. Four different types of joint intersections were found in which J1 and J2 forming intersection line dipping

away from the slope indicating it is a wedge failure. Using Slope Mass Rating method (SMR) field based Geotechnical investigations have been carried out to study the attitude of excavated slopes and measurements of discontinuities present in the rock mass accompanied by collection of representative samples. The final output derived with a value of 45 indicates that the slope is partially stable. Based on the data collected from field and lab analysis the slope stability of the landslide is computed using SWEDGE model. The results computed the total wedge area of the joint 1 is 297.33 sq.mts and wedge area for the joint 2 is 1587.52 sq.mts. The total factor of safety of this critical slope is derived as 0.9 which is below required value. A suitable economically viable measure been proposed like a Reinforced Wire Mesh Shotcrete as slope stabilization measure with an FOS value of 1.45 providing stability and support to negate the future occurrences of the slope failure.

Rock slope stability assessment along Minas road, Tons valley, Uttarakhand

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Slope stability analysis along the Minas road was carried out in a stretch of 40 km between Ichhari dam and Minas. Quartzite, limestone, sandstone and slates are the main litho-units. Geotechnical data for Rock Mass Rating (RMR) were collected from 39 locations for the classification of rock masses. The samples of different rock types of the study area were collected to determine the various strength properties. Discontinuity data collected at each location was plotted in stereographic projection and different types of slope failures (planar and wedge) were identified using kinematic analysis. Based on the types of failures 18 representative rock slopes were taken for the factor of safety (FOS) analysis using Hoek and Bray method (1981).

Based on the RMR study, it was found that out of 39 rock slopes, 14 rock slopes fall in good, 21 in fair and 4 in poor RMR classes. The kinematic analysis shows that 4 rock slope form planar failure, 14 wedge failures and remaining 21 rock slopes do not show any kind of slope failures. The strength analysis of the rock samples was carried out at laboratory through core samples as well as in field using Schmidt Hammer. The strength analysis reveals that the quartzite has highest Uniaxial Compressive Strength (UCS) followed by siliceous Bansa Limestone, purple sandstone, Deoban limestone and slate. The Factor of safety analysis shows that FOS value at 7 locations (L2, L5, L6, L7, L8, L9 and L10) is below 1 which represents unstable slope condition.

Large scale mapping and Kinematic analysis of vulnerable slopes along Sonprayag to Kedarnath, Garhwal Central Himalaya, India

Neeraj Ramola[1], Mohit Kumar Puniya[2], and Y.P.Sundriyal[1]
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In June 2013 due to continuous and high rainfall for about 72 hours from 15th to 18th June majority of the river valleys of Uttarakhand were flooded and hundreds of landslides created along National Highways, link roads, foot tracks and along the valley slopes, but the worst affected valley was Mandakini where about 7000 peoples lost their lives and a large number of infrastructures damaged severely. Out of 7000 people 90% people died in between Kedarnath to Sonprayag.

Main objective of the present study was to identify the active and potential landslide zones and to depict those zones on the large scale map (1:10000). With the help of the satellite data in GIS environment large scale map was prepared and the data collected from the field plotted. Kinematic analysis carried out to investigate the stability of rock slopes using rock science software. Further Rock mass rating (RMR) and Slope mass rating (SMR) has been carried out to identify different classes of slopes and Kinematic analysis to decipher the possible modes of failure in the study area.

Kinematics analysis of different slopes indicates that most of the failures are wedge and planar due to the presence of discontinuities (joints, shear zones, etc.). The values of RMR show that rock masses are categorized in II and III classes. SMR values are compliant with the failure of the slope and lie under bad to very bad slope classes. At some locations, loose/unconsolidated material also exposed that is also prone to slope failure. During present studies total 28 locations were investigated in which 12 locations were identified under stable class and 16 locations are found potentially unstable.

Spatial distribution of landslides vis-à-vis seismicity along the MCT in the Uttarakhand Himalaya, India

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Landslides are one of the most destructive hazards in the Himalayan terrain. It causes a serious threat to human lives, environmental degradation, road network, and infrastructures of the region. It has been noted that ~400 - 500 people lose their lives every year in the Himalayan region and monetary loss incurred in India is ~100 million $ per year. Generally, these are mainly triggered by heavy rainfall and high seismicity. The seismicity in the Himalayan region is mainly confined along the strike length of the Main Central Thrust

(MCT) zone. Therefore, it is hypothesized that there are a higher number of landslides as well, along the strike length of MCT. Therefore, the present study deals with the spatial distribution of landslides and the seismicity along a zone of 10 km on either side of the strike length of MCT in the Uttarakhand.

The study area exhibits 1772 active landslides in size of 25 m^2 or more and 689 earthquakes of $M_L \geq 2.5$. The landslides have been mapped using high-resolution satellite images and the earthquakes data used has been acquired by the WIHG broadband seismic network for the year from 2007 to 2015.

Spatial distribution of landslides and earthquakes plot clearly indicates higher seismic activity in these clusters namely near Uttarkashi (Zone-I), Chamoli (Zone-II), Munsiyari (Zone-III). Of these three clusters, seismic activity is highly concentrated in Zone-II, whereas in Zone-III the seismic activity is higher but scattered. However, it has been noted that there is a higher concentration of landslides in all three zones. Further, the quantitative correlation between the spatial distribution of landslides and earthquakes being continuing.

Multi-Criteria Evaluation Based Landslide Hazard Zonation of Mughal Road, Jammu and Kashmir, India

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Landslide Hazard Zonation (LHZ) mapping has been done by using Multi-criteria evaluation technique along the Mughal road from Shopian to Bafliaz. Landslide-related factors such as geology, distance to faults, drainage system, Land use/land cover, soil, elevation, slope angle, slope aspect were integrated in GIS (Geographical Information System) environment to delineate landslide hazard zones. All the factors were weighted on the basis of their relative contribution to the occurrence of landslides. These weights are normalized such that the sum of normalized weights is equal to unity. The resulting Landslide Hazard Zonation map identified five zones of landslide hazards, *viz.* very high hazard zone (3.8 %), high hazard zone (9.3 %), moderate hazard zone (43.42 %), low hazard zone (42.20 %), and very low hazard zone (1.1 %). The outcome was confirmed by relating with the landslide occurrences in different classes. The Multi-criteria evaluation model presented in this study could be utilized for other mountainous regions in general and Himalaya in particular.

Investigation of Road cut slopes Along National Highway-5, Shimla, Himachal Pradesh, North Western Himalaya

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Landslide is a natural hazard which carries mud, debris and large boulders under the influence of gravity. Shimla is the premium tourist destination of Himachal Pradesh, landslides in this region are the major cause of concern for the safety of people and infrastructure. In the present study, geological and geotechnical investigation of 14 rock slopes has been carried out along NH-5 near Dhalli tunnel, Shimla. The study area also includes one major landslide *i.e.* Dhalli landslide (Slope 3) which occurred on 2nd September, 2017. Kinematic analysis has been performed to identify the road cut slopes which have the potential to fail. Kinematic analysis shows that wedge failure (formed by J2 and J3) is the prominent mode of failure in Dhalli landslide. In this study to check the stability of road cut slopes, Basic Rock Mass Rating (RMR_{basic}), Geological Strength Index (GSI) and Slope Mass Rating (SMR) have been used. Slope 3 and 8 are highly unstable with SMR values <10, rest of the slopes are in SMR range from 10-35 which also comes in unstable category. It is indicated that unstable slopes become hazardous in the monsoon season and remedial measures should be applied in advance to prevent any major damage.

Study of Sibilong Landslide along Imphal-Jiribam National Highway (NH-37), Manipur, India

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The study area belongs to the Barak basin, forming an integral part of the Indo-Myanmar orogenic belts. The area exposes Miocene Surma sandstone with thinly bedded shale intercalations. The Surma sandstones consist of monocrystalline quartz, polycrystalline quartz, lithic fragments, plagioclase and K-feldspar. The rocks are highly jointed due to unplanned blasting operations. Significant anthropogenic interferences in the form of large scale excavation of natural slope for widening of the existing National Highway and disposal of excavated debris and waste material in the slope largely modifies the predisposal characters of the slope mass. The changes in land use make slope vulnerable due to reactivation of prominent triggering factors and reduction in the shearing strengths of slope forming mass. Both natural and human-related activities increase the risk for the landslide. Water from heavy and prolonged rainfall is a frequent trigger for the slide during rainy season. From the plasticity index of the soil samples, it comes under CL group suggesting slightly plastic soil of inorganic nature. The negative value of liquidity index (-1.176) and the positive value of consistency index (3.032), infers that the slope forming materials remain in solid state or semi solid state, indicating stable slope character. However, the soil column is

very thin and cannot aggravate the slide in the area. In the present study, uniaxial compression strength test and Brazilian test are used in order to assess the mechanical strength of the rocks of slide area. It is observed from the results of compressive strength that sample drilled perpendicular to the beddings give highest strength value comparing with those drilled parallel to the beddings which may be due to the presence of some structurally weak planar surfaces or some irregularity in the rocks that are practically not visible to the naked eye. From the SMR study, the rock class falls under class III of partially stable category. Susceptibility to failure due to rock discontinuities are demonstrated using kinematic analysis and SMR.

Stability Analysis for few Road-Cut Slopes along NH-58 near Kaudiyala and Shivpuri, Uttarakhand

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Himalayan ranges are considered one of the youngest mountain ranges in the world with a diverse lithology, geology, and tectonically most active ranges having a large number of unstable slopes. With the ever-rising anthropogenic activities, the threat of landslides either due to natural or road-cut slopes have risen. The present article focuses on the effect on the stability of rock slopes due to anthropogenic activities such as road widening and blasting carried along National Highway-58 (NH-58 connecting Haridwar-Rishikesh-Badrinath) as an outcome of the rising urbanization and pilgrim activities. Two sites, namely Kaudiyala and Shivpuri along NH-58, have been taken into consideration, followed by its geological and geotechnical investigations. Rock mass classification based on Rock Mass Rating (RMR) and Q-system was conducted on-site. Point load test on rock chunks was performed and based on the results obtained, UCS & shear strength parameters are derived empirically. Kinematic analysis based on Markland's test is performed to determine the possibility of slope failures. Finally, probabilistic analysis based on Monte Carlo Simulations has been performed. It is demonstrated how simple, inexpensive classification and characterization approaches can be used for arriving necessary data required for stability analysis of the rock slopes.

InSAR for landslide mapping: Experiences from Norway and Sikkim

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[1]*Geological Survey of Norway, Trondheim, Norway*
[2]*Norwegian Geotechnical Institute, Oslo, Norway*

For the last 15 years, the Geological Survey of Norway has been using satellite-based interferometric synthetic aperture radar (InSAR) to detect and characterize unstable rock slopes in Norway. Early results were based upon data from the 1990's, using the ERS-1 and

ERS-2 satellites. Despite the sparsity of available data (3-5 scenes/year), numerous unstable slopes were detected and subsequently mapped in the field. Between 2009 and 2018, the Radarsat-2 satellite was tasked to image the most landslide-prone areas of western and northern Norway. With more frequent and regular acquisitions, as well as higher resolution, the new data proved invaluable for landslide mapping. For the first time, artificial corner reflector networks were also deployed for year-round monitoring of unstable slopes.

The European Copernicus programme has provided new tools for global mapping of the environment. The Sentinel satellites are designed to provide global, free and open data, for now and the future. The Sentinel-1A and -1B radar satellites acquire global images every 6 or 12 days, depending on the location. This free data is revolutionizing the InSAR field.

In Norway, we have taken advantage of the newly available data to create a national 'ground motion' service. Ground movement data is provided for more than three billion locations. Since the release of the first national dataset, over 100 new unstable rock slopes have been identified. We have used the tools developed for this service to map ground motion throughout much of Sikkim province, from Gangtok north to Yumthang and east towards Changu Lake.

The most striking results from this project are within the urban areas of Gangtok. In addition to the well-known Chandmari sliding area, significant areas of movement have been measured in the Tathangchen, Burtuk, Sichey and Tadong neighbourhoods, as well as others. These sliding areas are heavily populated, with continuous new construction. We will show how InSAR can be used to monitor the deformation in these areas.

Risk Evaluation and Prediction of Rock Fall Prone Areas for Manikaran, Himachal Pradesh, India

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Several landslide in the form of rockfall occurred in Manikaran and surrounding area majorly due to rainfall and snow melting. In the year 2015, one major landslide occurred near Manikaran killing nearly more than 10 people and injuring 15 people sleeping in the shelter home. In 1980's India's first geothermal plant was set up at the right bank of Parvati river in Manikaran which was destroyed by the rock fall event. Gargi village is situated uphill approximately 1.5 km from the base of Parvati river. A constant rockfall happens in Gargi village especially during the monsoon season. The Manikaran - Bhuntar link road comes in the runout zone of rockfall is which the main route is connecting to the Parbati hydro electric project stage-(II) by NHPC Limited, a Govt. of India Enterprise. The landslide needs to be monitored in order to prevent loss of life and infrastructure in Manikaran town. Manikaran is a geothermal tourist attraction as well as holy place; it poses a potential danger for people and infrastructure which necessitates risk evaluation of this area. In the present study, RAMMS (rapid mass movement simulation) bare-earth and forested numerical modelling scenarios are conducted to evaluate the influence of natural factors on rockfall distributions. Different sites where maximum probability of rockfall was found on the basis of RAMMS simulations were marked for large scale studies which include geological mapping and characterization of the of rock mass. We use an integrated approach, which combines a consideration of geologic, geomorphic, and anthropogenic influences on rockfall distributions with field-based rockfall data sets and numerical modelling. We identified two source zones from where rock fall events initiate and poses a potential hazard for the people living in the valley of Manikaran town. For the real time prediction of rockfall events in Manikaran an early warning system is proposed.

Slope Stability Assessment of Landslide: A Case Study from Km 2 & 3 Slide Zone on Guptkashi - Kalimath Road on the Right Bank of Mandakini River in Rudraprayag District, Uttarakhand

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Landslides are defined as outward/downward movement of slope forming materials, which is a most common natural disaster in the hill regions. Landslides are dangerous and vulnerable which can be a resultant to the natural sequence of events like rainfall, earthquake, cloud burst and/or anthropogenic activities. In Uttarakhand, landslide activities are a major concern as the hilly portion of the state are characterised by the steep slopes consist of fill materials and weak rocks (i.e. weathered, fragile and shattered). Rainfall triggered landslides are quite common in Uttarakhand, here, in recent past landslide activities are increased due to excessive rainfall and unplanned road widening practices. Every landslide is different in nature; therefore it is necessary to study the landslide in detail to understand the causative factors responsible for the slope failure, furthermore to suggest suitable mitigation measures.

In present study the landslide site is located on State Highway (SH)-36 in Rudraprayag district of Uttarakhand. It is situated at an elevation of 1120.84m above the mean sea level having 30° 31” 52.35” N latitude and 79° 05” 16.78” E longitude. It lies on the right bank of Mandakini River at a distance of 2 to 3 km from Guptkashi town on Guptkashi - Kalimath road. The study area is a stretch of nearly 1,300 m along the road in zigzag fashion, where the slide is restricted within the single hill slope. The rocks exposed in the landslide zone are characterized by intercalated sequence of quartzite and schist with thin bands of amphibolites, belonging to Kalimath Formation. These rocks are highly jointed and fractured which indicates that the area is highly tectonised. Four sets of prominent joints and some random joints were observed in the study area. River Borne Material (RBM) is exposed along the hill slope below the road that extends up to the river level.

This study presents the detailed field investigations followed by the slope stability assessment. The field investigations include topographical survey, geological and geotechnical investigations. These studies were performed to understand the causative factors, failure mechanism responsible for the slope instability and dynamicity of the affected slope to formulate mitigative measures. Geological mapping was also carried out that includes mapping of joints characteristics and assessing different parameters which are required to quantify the RMR and Q classification systems. The kinematic analysis was carried out to analyze the potential failures which are likely to occur due to presence of unfavourable joint sets. Geophysical investigations like seismic refraction, multichannel analysis of surface waves (MASW) and electrical resistivity tomography (ERT) were also carried out and comparisons were made to confirm the subsurface lithology encountered at the site. Wave velocities obtained from geophysical results corresponding to different subsurface layers were also studied to know the subsurface geology and their characteristics. Trail pits were made to collect the samples from the site to determine the engineering properties and laboratory tests were conducted on debris and rock samples to evaluate the shear strength parameters.

Slope stability analyses were carried out for both static and dynamic conditions. On the basis of results obtained from the stability analysis, geotechnical and quantitative studies, the causative factors responsible for the slope failure were determined and various remedial measures for arresting the landslides were suggested like gravity bench walls, causeway, rock anchor supported retaining wall of various dimensions, scaling of loose rock mass, contour and toe drain, micro piling, channelization of nalas, gabions etc. as per site condition.

GIS based Landslide Susceptibility Mapping using Weighted Overlay Model

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Landslide is considered as the most destructive geohazard in hilly terrain region that causes human causalities, losses in property, effect the natural ecosystem and blocking the communication links. To overcome losses and damage due to landslides, various studies have been done on a landslide to specify more landslides hazardous areas. There are various methods and techniques are used for landslide susceptibility mapping using remote sensing and GIS. In recent years, the prediction of landslide areas with the development of advanced sensors can provide detailed information on a timely basis in a cost-effective manner, and more regions can be mapped in a sophisticated way. Remote sensing technology can be used for the detection and classification of landslide over large areas

In this study, digital elevation model (DEM) derivatives are considered for preparing the landslide susceptibility map. High resolution Carto DEM (10m) is used to analyse the terrain morphology and prepare the landslide susceptibility map. The DEM is a vital key in analysis for preparing such as topographic feature, runoff analysis and landslide susceptibility analysis. Landslide influencing factors considered in the study area are slope, aspect, relative relief, elevation, curvature, drainage density, distance from drainage. These factors used for the generation of thematic layers and then weights are assigned to each thematic layer using the weighted overlay model for the preparation of landslide susceptibility map in a GIS environment. Resulting map shows five categories: very low, low, moderate, high and very high susceptible zones. The final map validated using the successive rate curve and the prediction rate curve. The prepared hazard map provides useful information to the planner for development.

A Numerical Investigation of Micropile Reinforcement Effects on Stabilizing an Active Landslide in Uttarkashi District, Western Himalaya

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Landslides are one of the major natural hazards and very common phenomena in the Himalayas. Soil/rock slide, rock fall and debris slide are the most usual types of landslides which very frequently occur along the hill roads, not only disrupting the traffic but also causing immense loss of lives and properties. To mitigate such a hazard effectively, it is essential to develop a proper landslide mitigation technique so that the resulting damages can be minimized. There are many approaches to mitigate a landslide. These may include:

- Restrictions of development in landslide prone areas,
- Modifying geometry of slope, grading, landscaping,
- Landslide arresting works and
- Warning systems

The landslide arresting works include construction of structural elements like soil nails, cables, anchors, rock bolts, wire mesh, shotcreting, pile reinforcements and retaining walls. Micropiles which are one of the commonly used mitigating measures are in practice installed in arrays for slope reinforcement and stability improvement.

In the present study, the reinforcement effect and structural behaviour of micropiles in slopes have been addressed. For this, a model slope model has been built after collecting site data and performing stability analyses in two-dimensional finite element method. The study areas is chosen as an active slide, popularly known as the Netala slide, about 14 km from the Uttarkashi town, a district headquarters of Uttarkashi district in Uttarakhand and is located on the banks of river Bhagirathi. The Netala slide becomes very active during the heavy downpours on certain days in the monsoons every year and sometimes, the debris material and rock boulders roll down and block the road stretch which connects to one of the important Char Dam shrines, Gangotri Temple. The slide has significant height of overburden as debris underlain by weathered rock mass of Phyllite and Quartzite. The FEM model has been prepared based on a contour survey conducted and a critical slope section selected from the contour map. The slope model is then assigned the material properties of the debris and rock mass. Once the model is prepared, boundary constraints have been applied and gravity loading analyses is performed for both static and pseudo-static loading scenarios. The models have been analyzed and the factors of safety values have been computed for slope without and with different rows of micropiles. From the analyses, it was observed that the stability of the slope increases with micropile installation, although the degree of improvement depends largely on the rows of micropiles and spacing between them both in-plane and out-of-plane. Moreover, the analyses show that flexural rigidity of a micropile and numbers of micropiles in a group have great effect on the developed internal forces on micropiles and subsequently their design. However, length of micropiles and their in-plane spacing in a group have little effect on the internal forces developed, which is different from traditional anti-slide piles having large diameters. From these numerical investigations, it is established that the micropile reinforcement technique is an important and effective passive landslide mitigation method. If implemented, then this support scheme will be able to minimize the sliding activities at this site.

Large scale Remote Sensing Analyses of Slope Instabilities

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The small Himalayan country of Bhutan is characterised by rugged terrain, high topographic gradients and a variety of climatic conditions. These factors contribute to make the country prone to different phenomena leading to slope displacement. Despite its proneness, to the best of our knowledge, no comprehensive slope instability inventory existed before this work begun, that could serve as a basis for future landslide hazard assessment, or to inform land use management practices and to investigate the regional distribution of large landslides. We show the results of analyses that are largely based on remote sensing techniques to overcome the inaccessibility of the region. These analyses leverage a combination of optical images analyses, DInSAR (Synthetic Aperture Radar Differential Interferometry) single interferograms and DInSAR multi temporal analyses. We present new datasets of unstable slopes characterised by displacements in the period between 2006 and 2011, with a likelihood of activity and a geomorphological classification which allows to identify different types of landslides as well as rock glaciers. We show another new inventory based on DInSAR multitemporal analyses, which illuminates not only rock slope instabilities and rock glaciers quantifying the creep velocities at the regional scale, but also reversible deformation associated with freeze-thaw cycles or groundwater table variations. We also propose a new inventory of past large rock slope instabilities based on optical images and DSM analysis and a large structural dataset articulated on a variety of sources, but largely retrieved from remote sensing data. Our inventories, analysed in combination, suggest that recent landslide activity appears to be lower than it may have been in the past. We also identify structural and lithological control on rock slope instabilities across some parts of the study region, with higher predisposition to failure likely associated to the presence of specific sets of regional faults, foliation/bedding structures and specific lithologies. Our analyses are replicable and applicable to other mountainous regions and potentially leading to results that constitute a basis for regional landslide susceptibility mapping for hazard mitigation purposes.

Comprehensive Solution for Amparav Landslide

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Uttaranchal state is one of the Indian Himalayan States experiencing many natural hazards such as flash flood, earthquake, landslides, avalanches, forest fire, extreme events etc. due to its geological, geomorphological and environmental conditions. Since, landslides are the most common hazard and recurring in nature, damaging many civil engineering structures and responsible for nonfunctioning of hill roads, especially during rainy season. Therefore, detailed landslide investigation and remediation of unstable slopes is required to make landslide free, roads in Himalayan states. Amparav landslide is one of the landslides, which occurred at three places on 23th September 2004 in Amparav area, Nainital District, Uttaranchal, responsible for the loss of life and damages of civil engineering structures such as foot-over bridge and National Highway-87, besides the other losses in the area. Two major landslides occurred in talus material on higher reaches and another one is rotational failure took place at lower region, both damages NH-87. Therefore, in order to stabilize the area, comprehensive solution is required. An extensive field work has been carried out to cover a small watershed about 3.0 sq. km. Identified watershed area has been mapped on 1:100 scale with 1.0 m contour interval to cover all geological, geomorphological and landslide features present in the area. Based on field as well as laboratory work, comprehensive solution in terms of series of remedial measures are designed and suggested to stabilize the area. Present paper includes the detailed study and provides a series of remedial measures.

Different Sets of Remediations for Mitigation of Landslides adjacent to Roads in Himalayan Terrain

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The great Himalayan Mountain is a majestic cluster of several numbers of more or less parallel hill ranges intervened by numerous valleys and extended plateaus. The Himalayan landscape, as said by expert geologists, is especially susceptible to landslides. The northward movement of the Indian plates caused continuous stresses on the hill slopes making it weak and prone to landslides. The Himalayan topography, as well as high seismic vulnerability and rainfall in the region, are enlarging the liability to landslides. Landslides or landslip involve a large ground movement due to the gravity forces which results in total mass wasting of the slope. The landslides are experienced in almost all the National and State highways adjacent to the hill slopes of the Himalayas and hill ranges of India North East, Western Ghats and Nilgiris, Eastern Ghats, Himachal, J&K, Garhwal & Kumaon hill ranges and Vindhyas. The remedial measures for landslides may be divided into four subcategories; restraint, removal, drainage, and relocation. The retaining structures are designed to retain rock/soil slope that it would not naturally be stable at its position. The reinforcement measures include soil nailing & earth reinforcement measures which involve the insertion of steel rods, metallic strips, geosynthetics, and steel angles to improve the stability of the slope. The reinforcement measures also include the improvement of the mechanical characteristics of the ground through chemical, thermal, or mechanical treatment. The third major remedial measures are drainage measures which are most effective in a geologic condition that allows interference with the natural water regime. Also, bioengineering techniques in which vegetation is a fundamental part are useful approaches to prevent landslides as they improve slope stability and maintain ecological balance. They are most suitable to be deployed in developing countries because of their cost-effectiveness and environmentally friendly nature. The chosen remedial measures depend upon several factors such as type movement (slide, flow, etc), type of material (debris, rock, soil, etc), location of the failure, the process of failures, etc. Several factors that are to be considered before designing and implementing landslides remedial measures will be discussed in the paper.

The paper shall be dealt with a different sets of remediations such as soil nailing technique, earth reinforced structures, retaining structures, drainage measures and bioengineering technique for mitigation of landslides adjacent to roads in Himalayan terrain considering the economic as well as social feasibility, steadiness, and efficiency. Moreover, several advantages and disadvantages of remediation techniques shall be incorporated in the paper.

Investigation and Remedial Measures for Landslide in Rati Ghat NH-109, Uttarakhand

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Landslide is one of the major geological hazards in Himalayan terrain of Kumaun region uttarakhand and is one of the primary reasons of environmental degradation of this region. It poses serious threat to the infrastructure and socio -economic condition of people of this region. It is estimated that 30% of the world's landslide occur in the Himalayan terrain and monetary loss incurred in India is Rs. 700 crore (100 million $) per year.

The landslide in Kumaun region of Uttarkhand mainly cause by combination of both natural and the anthropogenic factors. These are also accompanied by others hazards like earthquake that greatly affects and threatens major part of Kumaun region Uttarakhand. Over the past few decades the weather and climate -related disaster in this region have increased many fold, primarily due to altered precipitation. The recent climate projection for future also indicate a significant increase in frequency and/or intensity of extreme events and thus the landslides in the regions. This is further exacerbated with the ever increasing urbanization and development during recent years in Himalayan terrains.

The objective of the above study is asses the probable reason (slope angle, slope aspect, slope curvature, vegetation, meteorology, geology) for landslides in this particular region. Further slope is numerically modeled in slope/w (Geostudio) and stability number is computed and compared by several methods (Swedish, Bishop, Janbu's). Later result is being verified manually by developing Excel spreadsheet module. After validation of results and comparing results of different methods certain remedial methods are being suggested and their economical analysis is being done.

Mapping, Hazard and Consequence Analyses for Unstable Rock Slopes in Norway: experience from 15 years of Systematic Mapping

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Systematic mapping for unstable rock slopes that can cause catastrophic failures has been carried out in Norway since 2005. In the first years, a systematic mapping approach was developed that includes focussed first on a hazard and second on the consequence analysis. The first combines morphological signs of rock slope deformation, structurally based stability considerations, the state of slope activity and past events to come up with a hazard score and defines 5 hazard classes. The second includes for all unstable rock slopes the analysis of the volume, the potential run-out area and for those where applicable the assessment of related displacement waves in case that the failure hits a fjord or lake or the assessment of the landslide dam in case that the failure would reach the river valley. The consequence assessment is to assess the potential loss of life for possible failure scenarios, impact on the infrastructure is not included. The hazard and consequence analyses are used to define high risk sites and for hazard zoning in relation to the Norwegian building codes. So far, more than 500 unstable rock slopes have been found, of which 110 were hazard and risk classified. 48 of the slopes have hazard zones and thus result in building restrictions and seven sites are today under continuous surveillance, a task carried out by the Norwegian Water and Energy Directorate.

Investigation of correlation between RMRbasic and CSMR using global dataset of joints and slope facets: case study from NW Himalaya, India

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Geological and geotechnical investigation of 35 slopes is conducted along national highway (NH-58) from Srinagar to Rudraprayag, Uttarakhand, India. For the slope facets in the study area, basic rock mass rating (RMRb) and continuous slope mass rating (CSMR) is calculated, which shows no correlation between RMRb and CSMR (correlation coefficient, R^2= 0.18). In this paper, we investigate the main factors which affect the correlation between RMRb and CSMR. For this global dataset of joints and slope relationship is generated and simulations of all possible cases are investigated. Results obtained from this analysis demonstrate that maximum drop in CSMR from RMRb is 60 in case of planar/wedge failure and 25 in case of toppling failure (for any value of RMRb). Therefore, it is concluded that RMRb and CSMR will show good correlation in areas where toppling failure is the dominant mode of failure. Whereas, planar/wedge failure will produce maximum scatter in the RMRb and CSMR plot, hence disturbing the correlation between two stability assessment methods. Different types of correlation between RMRb and CSMR for planar/wedge and toppling cases are discussed with its application in mountainous terrains.

A frame work for Debris flow Hazard Assessment in Garhwal Himalaya, India

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Debris flows are frequently occurring events in Indian Himalayas. Debris flows are mixture of water along with finer particles such as silt and clay and coarser particles such as sand, gravels and boulders which travel down the slope due to gravity. The main driving force for occurrence of debris flows in Indian Himalayas is rainfall; however, seismic activity is also observed to be responsible for such phenomena in the recent past. The tectonic complexities, extreme climatic conditions, steep slopes, and antropogenic activities in the Himalayan region are the reasons behind the recurrence of debris flow events. Considering the ever increasing debris flow hazards in Garhwal Himalaya, a frame work for its assessment has been proposed and carried out in the present study.

For debris flow hazard assessment, a three-step methodology has been proposed. Firstly, detailed mapping of potential debris flow sites along NH-58 in Chamoli district of Garhwal Himalaya has been carried out. Subsequently, debris flow hazard map has been prepared based on the nature and intensity of debris flow, frequency of debris flow and availability of

the materials at the source zone. Finally, a detailed study on site specific debris flow modelling approach has been performed to generate the quantitative information on debris flow intensity parameters. In this paper, an approach for debris flow hazard assessment has been given and also a case study from Chamoli district of Garhwal Himalaya has been illustrated. Runout modeling has also been considered to include the hazard intensity factor in debris flow hazard assessment.

A Comprehensive study of Dungale Landslide, Tons Valley, Uttarakhand

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Landslide is the most widely spread natural hazard in the Himalaya, which poses serious threat to people and various infrastructures. The Government of India and state agencies are incurring, crores of rupees to investigate, monitoring and to adopt mitigation measures to stabilize these landslide affected region along with rehabilitation of villages. The area is being stabilized when constructed engineering structures offer the precise amount of resisting forces to the slopes in stresses. In order to evaluate the stresses conditions, proper geological and geotechnical investigations of concerned landslide along with numerical modeling is required, avoid of these could lead to failure of engineering structures as of reactivation of landslides. It is thus essential that any engineering construction in landslide affected areas should be well planned based on the detailed geological and geotechnical investigations prior to adopting mitigation measures.

The Dungale landslide is choosen for the present study which is situated along the left flank of Tons valley at at Longitude 77º 47' 44"E and Latitudes 30º 31' 43"N. It lies at about 14 km north of Kalsi township in Dehradun district of Uttarakhand and at close proximity of Ichari Dam Site. The vast portion of agricultural terraces situated at the crown of this landslide has been severely affected by landslide activity in 2013 and hence blocked the State Highway running across the landslide by accumulation of 27119.36 m^2 slope wash material. The presence of tensional cracks at crown of landslide exhibit the active nature of this landslide and hence need to be study in detail.

A detailed field and laboratory investigations are being carried out of Dungale Landslide which includes GPR Survey, Drone modeling using Agisoft and geotechnical investigations of slope forming material. Slope stability analysis were carried out using "Slide 4.0" and "RS2" based on Limit equilibrium method and shear strength reduction method respectively, on the cross section of dungale landslide obtained from 3D modeling of drone images and factor of safety be determine. The preliminary result suggests that only the upper portion of slide is under stress with factor of safety <1.

2014 Jure Landslide in Nepal - a Disaster of Extreme Tragedy

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Subduction of Indian Plate beneath the Eurasian Plate has evolved high Himalayan mountain chain that covers about 2500 km stretch from the Karakorum in the west to close to Myanmar in the East. In contrast, the width of the Himalayan range extends barely about 200 km within which the altitude varies from approximately 200 m above the sea level to over 8000 m including the top of the world "The Sagarmatha" having elevation 8848 m above sea level. Substantial increase in height within relatively short distances has made Himalayan mountain topography very rough and steep. Hence, the river valleys are narrow where people reside. Himalayan region is known to be very dynamic due to active monsoon and frequently occurring earthquakes of different magnitudes. The numerous North to South following rivers cross-cuts the mountainous topography leading to extreme erosion along the valley slope during every monsoon. Both monsoon rain, large variation in the temperature over the year and frequent earthquakes make Himalayan rock mass weather relatively fast. As a result, frequent landslides occur in the Himalayan area, especially during the monsoon period and on some occasions during large scale earthquakes. More importantly, the earthquakes are the catalyst for the large-scale landslides since long persisting discontinuities are formed during the earthquake episodes. Frequently occurring landslides are common in the Himalayan region, which kills many people every year and society in the local area is devastated. A famous living memory of an example of landslide induced devastation in Nepal was the landslide at the Tinau river that took place in early September 1981, which dammed the Tinau river completely and the dam was breached causing the huge flood to the downstream valley. The flood swept away the concrete tower of the Tinau Hydropower Project, swept away two suspension bridges and one concrete bridge at the city of Butwal. The part of the Butwal city was completely damaged by the flood killing many hundreds of people. Similarly, on the night of 1st August 2014, a huge landslide, famously known as "Jure Slide", took place along the Sunkoshi River valley on the Araniko Highway that connects Kathmandu with Tibet. The slide killed 156 people who were in deep sleep in their respective houses. The landslide completely savaged 120 houses and partially damaged 37 more. The landslide also dammed the Sunkoshi river by creating a dam of approximately 50 m high with a base width of about 500 m. An approximately 2 km long reservoir was created as a result. A huge flood occurred after the partial breach of the dam, which damaged the barrage structures of the Sunkoshi Hydropower Project located about one kilometer downstream from the slide area. It took almost two months to drain the artificially created reservoir and the Araniko Highway was closed for about 6 months. The scar of the slide was seen for many years which is believed to have been created by many episodes of earthquakes developing a deep failure plane within the rock mass daylighting the plane just above the Araniko Highway of Jure village near Lamosangu. This presentation is devoted mainly on the Jure slide. Critical aspects of the slide will be highlighted giving emphasis on topography, geology, rock mass, monsoon and earthquake.

Investigation of Slope Failures in Western Ghats integrating Mobile based Site inventory and advanced Geospatial techniques

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Landslides have turned out to be one of the most disastrous natural hazard. The increased anthropogenic activity in hill slopes augmented by extreme climate events such as severely heavy rainfalls trigger landslides as most destructive natural disasters for mankind in the recent past. Western Ghats is no exception to this which is evident from the extensive damages caused by landslides during the past consecutive monsoon seasons of 2018 and 2019. Triggered by severe rainfall, the slopes of Western Ghats along North Kerala experienced deep-seated landslides whereas the slopes along South Kerala are affected by shallow flow – type landslides termed as debris flows. This study aims at proposing an outline for improved landslide mapping and monitoring using advanced geospatial techniques, evaluating current understanding and appraising the knowledge gaps on landslide hazard assessment based on specific site investigations along Western Ghats. The fundamental task of landslide research is collection of *in situ* field measurements. In an era of technological progress inspired by revolutionized telecommunication, the android mobile-based "GeoMAPP" application utilizes inbuilt mobile GPS to Geo–tag the location and enables live data transfer to the centralised server. This would entail the local community as part of citizen science initiative for active participation in landslide data collection using the mobile App displayed through a Web Map Service. The availability of high resolution optical and Synthetic Aperture Radar (SAR) imagery enables mapping and updation of landslide inventory scoping for improved hazard susceptibility and zonation analysis. Further, the development of Radar Interferometric techniques potentially enable monitoring of the slope instabilities using time series SAR Interferometry. The slope failures that occurred during the monsoon season of 2018 and 2019 over the Wayanad – Nilambur belt of north Kerala have been spatially mapped using the Sentinel 2A Multi Spectral Imager (MSI) and validated with site investigation using the GeoMAPP application. The performance of available statistical landslide susceptibility methods over Wayanad region has been assessed using high resolution topographic data (AW3D 5m DTM) appropriately scaling up all contributing causative factors thus evaluating the scale dependency of topographic variables on the accuracy of various susceptibility methods. The identification of rainfall events responsible for landslide occurrences in Wayanad is being attempted using satellite derived precipitation data for constraining the regional empirical rainfall thresholds utilizing cumulated rainfall-duration relationships. Site-specific field inspections augmented with ground based Terrestrial Laser Scanning provides comprehensive spatial information on the dynamics and kinematics of the Kavalappara landslide of Nilambur, Malappuram District in Kerala. This study has evolved an operational framework for landslide mapping, monitoring and hazard zonation using advanced Geospatial techniques. The integration of the android-based mobile application into landslide site inventorying enables state-of-the-art multi-disciplinary susceptibility mapping approach, which can provide better understanding of process, leading to hazard forecasting, thus reducing the risk and ensuring secure life.

Q Slope method in Rock Slope Engineering: Modifications and case study from the Himalayas

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Active geodynamics, major structural discontinuities, high earthquake vulnerability, and occurrence of heavy rainfall often with cloud burst events pose significant slope instability problems. Anthropogenic factors like unscientific, inadequately executed, and faulty techniques during construction and excavation for roads, railways, tunnels, and any other civil engineering structure escalate immense mass movement phenomena in the region. Large scale landslides along road cut slopes cause lots of injuries, fatalities, loss of property, disruption in traffic and Char Dham yatra which are of great concern. To achieve much safer and economical design, careful monitoring of vulnerable sections is a prerequisite for the swift development of socio-economic activities. Structurally controlled failures by forming planar, toppling and wedge types of failures are quite common along transportation corridors of the Himalayan region. The present study was intended to evaluate the hazard potential of road cut slopes along national highway-58 from Rishikesh to Devprayag. Q Slope method has been applied to 20 vulnerable sections along the highway. Q slope values of investigated slopes range from 0.0023 to 0.7849 indicating a high potential of failure along the highway. To attain safe design along the highway, stable slope angle without any reinforcement (β) have been calculated for probability of failure 1%, 15%, 30% and 50%. The stable slope angle determined by the Q Slope method was also compared with the outcomes of numerical simulation and some remarks have been added in the stability chart. Furthermore, by considering the failure mechanism, some modifications have been suggested in the Q Slope equation. The outcomes of the study can be utilized in ongoing road widening and development of the Char Dham route. Such slope stability analysis techniques provide a quick and cost-effective estimate of stability grade that can be utilized for detailed evaluation, planning, and execution of sustainable geo-engineering projects.

Geology, Tectonics, Causes and Mitigation of Landslides in the Sikkim Himalaya, India

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Landslide is one of the most common and main geohazard in the Himalayan state of India in Sikkim, Northeast region. High spatial and temporal variability of landslides in Sikkim Himalaya may be attributed to lithological variation as well as magnitude of structural deformation in the form of various large- and small scale structural features viz. thrust, faults and small -and large scale folds. Apart from these planar features like joint planes,

schistosity and axial planar cleavage are some of the important geological factors in controlling the prevalence of landslides. The Spatial and Temporal variation also shows that frequency of landslides is higher in eastern part of Sikkim Himalaya. However, the intensity of Landslide has been noticed higher in the northern part of Sikkim. In addition to these geological and tectonic factors, high rainfall, steep topographical slope, and high weathering rate are other major contributory factors for the landslide prevalence. Rainfall in Sikkim Himalaya contributes a major role in generating landslides in different parts of state. High intensity of rainfalls is related with debris flow. Most landslides in Sikkim Himalaya occur during the southwest monsoon. The seasonal variability of the landslide has a good correlation with the progress of the monsoon. The real-time monitoring of prevailing weather and early warning systems may be installed in all the districts of the Sikkim state to minimize the landslides. Natural disasters such as landslides, earthquakes and floods etc. inflict severe damage to human lives, ecology and economy of a region. India has installed new space technologies as INSAT and IRS series of satellites for disaster warning, especially cyclone and drought, and their monitoring and mitigation. However, such techniques in the Sikkim Himalaya will be helpful to predict certain events like earthquake , seismogenic landslides, flash flood including Glacial Lake Outburst Flood (GLOF) since it is located in the seismic zone IV of India. There has been a major earthquake in 2011 in West Sikkim near Nepal border close to Main Central Thrust (MCT) and requires further geological, seismotectonic and geophysical investigations to understand the origin of landslides in the Sikkim Himalaya. Landslides are frequently triggering along the National Highway 10, therefore, the construction of roads and dams along Teesta River must be constructed with great care and modern technology, keeping in mind the geological instability of the area. Bioengineering solutions for the mitigation of the landslides applied in Nepal Himalaya and suggested earlier for the Uttarakhand Himalaya would be very useful in the Sikkim Himalaya.

Geotechnical Characteristics and Stability Assessment of Rock Slopes: A Case Study from Lesser Himalaya, Uttarakhand

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The Himalaya region in India is highly vulnerable to landslides because of tectonic movements and its complex geological and geotechnical conditions. A landslide is mass movement of soil/rock materials down the slope of a hill due to gravity. When the rocks moved down the slope, it is called as rock slides/falls/topples. Rock falls are major concern in steep mountainous regions under poor geological and geotechnical conditions especially in Himalayan region. The Himalaya is characterized by jagged and dissected ridges with lofty mountains. In the present study rock slopes situated near Koteshwar dam site in the district of Tehri, Uttarakhand has been considered. The slopes are characterized by steep slopes exhibiting extensive geological discontinuities and physical weathering. The main rock type observed in this area is Phyllite. The aim of the present study is to characterize the

engineering properties of rock mass and then performing stability analysis. Laboratory investigations have been performed on Phyllite rock samples collected from rock slopes. Laboratory tests like ultra sonic wave velocity, point load, tensile, and uniaxial compressive strength were performed on rock samples. Data pertaining to discontinuities and their behavioral characteristics was collected during field investigation which was used to estimate the RMR, Q and GSI classification systems. The results obtained from lab tests and field investigations were used to evaluate the shear strength parameters of the rock mass. During the field investigations, geological mapping has also been carried out and this was used for the kinematic analysis to check the possibilities of failures in the rock slopes. Finally, stability analysis of rock slopes has been carried out using finite element software, RS2. The results obtained were used to identify rock fall risk in the study area.

Disturbance affects forest composition and structure in Himalayan ecosystems: an assessment in Nanda Devi Biosphere Reserve

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Landslides are the frequent disturbance events in the Himalaya that affect various ecosystems along the elevational gradient. The consequences include removal of topsoil and disruption of stabilized communities. The significantly altered nutrient pool in these degraded habitats negatively impacts vegetational re-growth. In order to facilitate the restoration of these degraded ecosystems, it is important to understand the post-landslide natural colonization by analyzing the correlation between the vegetation structure and the soil properties of these degraded ecosystems on a temporal scale. We carried out field studies in and around Bhyundar and Pushpawati Valley (Valley of Flowers) areain the Nanda Devi Biosphere Reserve region in upper Alaknanda River Basin of Uttarakhand, India. Plant community structures of 10 landslide disturbed sites representing a chronosequence of 1, 2, 3, 5, 7, 15 and 25 years along an elevational gradient between 2500 and 3500m were investigated using nested quadrat method. The neighboring undisturbed forest community served as the control. We recorded 280 angiosperm species from the depositional areas of the landslide disturbed sites. The lower elevations were dominated by exotics such as *Conyza bonariensis, Sonchus oleraceus, Ageratina adenophora, Alnus nepalensis*, *Fagopyrum esculentum* and native weeds like *Phytolacca acinosa*, *Koenigia mollis* and *Calamagrostis emodensis*. *Scrophularia edgeworthii* and *Gaultheria nummularioides* were the dominant pioneer species at the middle elevation landslides. Along the late successional sites at the higher elevations, majority of the colonizing species were natives such as *Geranium wallichianum, Galium aparine, Morina longifolia, Koenigia tortuosa* and *Anaphalis contorta.* Ruderals like *Polygonum polystachyum* and *Rumex nepalensis* with a high invasive potential were predominantly occurring the same native habitat. The herbaceous flora dominated the younger landslide sites (highly disturbed) while tree vegetation increased with the increasing age of landslides with shrub flora dominating the landslides of less than 10 years.

Landslide Susceptibility Mapping of Kashmir valley using GIS based data methods

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Landslide hazard is the potential for a landslide to cause damage and landslide risk shows how vulnerable or the potential for loss an area has due to a landslide. It is one of the geological hazards with respect to Kashmir Valley, which damages the human lives and properties as Kashmir valley falls in the Himalayan range, which is more vulnerable to landslides. In this work, landslide susceptibility zones for Kashmir valley has been studied using the multi-criteria approach techniques such as Analytical Hierarchical Principle (AHP), Frequency Ratio and Fuzzy Logic with Landslide Numerical Risk Factor. More than Hundred Landslides have been identified and a landslide inventory map has been prepared. The Landslide Inventory Map has been prepared using many geo-environmental datasets, such as slope, elevation, aspect, rainfall, geology, soil texture, land use land cover, lineament and lithology using Arc Map Software. Land Susceptibility Maps were prepared based on the Landslide Numerical Risk Factor, Frequency Ratio and Fuzzy AHP in a GIS Environment. The aim of this mapping was to identify areas pre disposed to landslides which occurs in the region of Kashmir. Thıs study will be very useful in understanding the landslide hazard events and can be used in national land use management plans.

Geological and Geotechnical Studies of Vulnerable Slopes along National Highway- 58 (NH-58) Srinagar, Uttarakhand, India

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The failure of rock slopes along the roads in fragile belt of Himalaya is a very common and critical geological problem. Landslides that happened after Uttarakhand floods in June, 2013 have been creating problems on the strategic National Highway- 58 (NH-58). NH-58 is the main route for well-known pilgrimage sites such as Badrinath, Kedarnath and Sri Hemkund Sahib which keep the road extremely busy. However, there is also an ever-increasing demand of land for urban development and mega-projects such as ongoing railway project from Rishikesh to Badrinath making inhabitants to adapt and survive at dangerous slope margins. In a view of huge societal importance of the problem, landslides in the study area poses serious threat to ongoing traffic and all activities that are related to social and economic well-being of Kumaon and Garhwal Himalayas which are dependent on the established road and highway network. All vulnerable slopes needed to be stabilised through various engineering and bioengineering means in order to protect the living standard of hill people against the increased rate of slope degradation. The area experiences landslides every year and such problems are reported in huge numbers due to geodynamic nature of Himalayan region. In the present study, stability analysis of the of road cut slopes along the Alaknanda

valley of Dudatoli and Garhwal Group between Srinagar and Rudraprayag on National Highway-58, Uttarakhand has been carried out. Geological and geotechnical methods have been employed to understand the behaviour of slopes. Kinematic analysis has been performed on the slopes to check possible failure modes. In order to check the quality of rock mass along the NH-58, various rock mass characterisation methods such as Geological Strength Index (GSI), Rock Mass Rating (RMR), Slope Mass Rating (SMR) and Continuous Slope Mass Rating (CSMR) have been employed. Unstable and stable slopes in the study area have been identified and characterized based on SMR and CSMR.

Landslide Hazard, Vulnerability and Risk studies using multi-criteria decision-making (MCDM)

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In India, landslides are the most frequently occurring disaster in the regions of the Himalaya and the Western Ghats. They are mainly triggered either by rainfall or earthquake or the combination of both, causing severe damage to human life and infrastructure. This study presents a comprehensive use of the multi-criteria decision-making (MCDM) method in landslide risk assessment for the Tehri area in the state of Uttarakhand, India. The Tehri area is situated in the Lesser Himalaya of Garhwal hills lies in zone IV of the seismic zoning map of India. Because of the large-scale slope instability in the area, it has received the special attention of the researchers. In the recent past, many landslide hazards and risk zonation is carried out for different regions in the Uttarakhand state. However, limited work is done considering temporal factors such as seismic ground shaking, rainfall, seismic amplification at surface level. The DEM data is used to produce topographic characteristics such as slope, aspect, relative relief. DEM data is also used for the detailed drainage analysis which includes topographic wetness index (TWI), stream power index (SPI), drainage buffer, and reservoir buffer. Seismic hazard analysis is performed using the deterministic methodology to estimate the peak horizontal acceleration. The amplification factor is calculated using the non-linear site amplification method. In this study, the analytical hierarchy process (AHP) is used to evaluate the landslide hazard index which is used to generate landslide hazard zonation (LHZ) map. Further, the landslide vulnerability assessment is done for the study area. The vulnerability map of the study area is derived in terms of land use/land cover (LULC) using remote sensing data of Landsat 8 which can provide useful information that helps people to understand the risk of living in an area.

Geohazard Mitigation Solutions for Himalayan Region and similar geology

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Landslide is a common natural phenomena experienced in hilly regions and mountain flanks and the Himalayan region is a home to a fair share of these hazards. These calamities strike here quite frequently and end up claiming a huge toll in terms of loss of human life and infrastructure. This kind of large rock mass movement along the slopes of these steep slopes, coupled with other natural factors can also strike with some ugly variations – loose soil collapse due to rains, rock falls/shooting due to freeze-thaw actions of seeping water, debris flows along channelized paths and avalanches if the moving mass is snow. These fatal threats are quite prevalent now, and will only continue to increase with climate change, cutting of hill slopes and developments in hilly areas. All these instances call for our immediate attention to be addressed with reliable mitigation measures. We, at Geobrugg, are actively involved in designing and manufacturing a variety of solutions specially catered to contain the damages caused by aforementioned calamities. These solutions are specially designed depending on the topography, location and problem statement of the hazard. The innovative solutions arrest the geohazards ensuring long-lasting and sustainable protection, both environmentally and aesthetically pleasing. GEOBRUGG was founded in Switzerland in 1951, has been working – since the beginning until now – in the field of prevention against natural hazards. Since 1970, GEOBRUGG AG - Protection Systems is part of the Swiss BRUGG Group, which incorporates also further internationally leading companies, situated in the business of fabrication and commerce of cables in all its different varieties. The experience of GEOBRUGG in various countries of America, Africa, Asia (Indonesia, Malaysia, Singapore, China, India, Japan, Philippines, Taiwan), Australia, New Zealand and Europe shows that GEOBRUGG's flexible protection systems comprise an ideal behaviour for the intended protective purpose – thanks to the high resistance of their components and the system's characteristics. At the moment GEOBRUGG is worldwide present in 50 countries and has successfully realized projects in over 60 different countries and can count on own production plants in Switzerland, USA, Russia, Japan, China and Australia. In this paper, a comprehensive view of the entire product line of Geobrugg in India will be presented, along with the past installations (both Indian and abroad), showcasing the variety of clientele involved. This will provide a more practical insight of the systems in action and feasibility of the systems.

Delineation of sub-surface Water channel on a Slope using 2-D Electrical Resistivity Tomography

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Debris flow is known to be highly susceptible to the influence of both surface run off and subsurface water. The presence of water can increase or decrease the risk of debris flow depending on the nature and amount of water present within the slope materials. The delineation of subsurface water channel in Tangni landslide has been investigated using 2D electrical resistivity tomography. To understand the path and nature ofthe underground water in the failure process of the slope located along NH 58, Garhwal Himalaya, India. The influence of subsurface water cannot be overlooked in slope investigations. It has been established that water is a critical factor in slope stability. It increases the unit weight of material as well as both the normal and shear stress of the slope. It can also create pore pressure which opposes the normal stress therefore reducing the resisting forces of the slope material. Therefore, it is essential to study the influence of sub-surface water on slopes. ERT has been known as one of the tools in uncovering the location of water path and saturated zones of the slopes. This method has revealed that there is underground water channel at the centre of the sliding body below 25 m from the surface. This was also witnessed at the road level. Drainage measures along this path will be helpful to reduce the impact of slope failure at the road level.

Flash flood Susceptibility Mapping in a Mountainous basin

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The geological and metrological (climate change) mechanisms are generally associated with flash floods events in the mountainous river basins, *e.g.* heavy precipitation, cloud burst, glacial lake outburst flow (GLOF), landslide lake outburst flow (LLOF). A flash flood event may have a lower frequency, yet, it carries out maximum geomorphic work, *i.e.* erosion, deposition, and transportation of sediments. The global occurrence of flash flood events highlights the importance of developing a robust approach for predicting susceptible river reaches during such events in a mountainous basin.

In the present study, we choose the Upper Ganga River catchment (UGRC) (~ 20,000 km^2) as a test site to study flash flood events between the years 2011 and 2014. To extract flash flood susceptible river reaches in the UGRC, we used normalized steepness variability of longitudinal profiles of the streams in the UGRC. The streams analyzed for variation in their steepness along the length, and segments susceptible to flash flood events showed either

erosion or deposition during the event. Our results show that several rivers reach in the UGRC are susceptible during a flash flood event. We present five highly sensitive river reaches in the UGBC *i.e.* Asiganga, Bhilangna, Mandakini, Garudganga, and Alaknanda Rivers that are susceptible to changes during a flash flood event. We also carried out the geomorphic analysis for the years 2011 and 2014 in the selected reaches to strengthen our results. Such a new technique will provide a unique and robust flash flood susceptibility mapping, from which river sensitivity on geomorphic adjustment towards such extreme hydrological events can be predicted in the future.

Basin-wide Approach to Landslide Hazards Assessment and Deployment of Early Warning System in Sub-Basins of River Rora Chu in Part of Gangtok Region, East Sikkim Himalaya

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Sikkim has a history of landslide hazards with more than a thousand landslides been so far reported in a span of few decades, leading to distressed life and huge recurring economic loss. It receives heavy to extremely heavy rainfall which has been projected as a major contributing factor for inducing large number of slope failures and landslides. Besides, Sikkim Himalaya is also tectonically active with major thrust faults crossing the area and triggering intermittent earthquakes of varying intensity. Therefore, hilly terrain of Sikkim is prone to multiple geohazards induced by heavy rainfall, earthquakes or combination of both that have produced dominantly debris cum rock slides, rock falls and complex types of landslides respectively. Compounding the vulnerability are the adverse human interventions such as unplanned urbanization in such fragile mountainous terrain, improper management of drainage, inadequate treatment of hill slopes prior to construction and widening of roads, etc. All these factors tend to accelerate the process of mass movements in the area investigated.

The perennial Rora Chu River flows from NE to SW, draining precipitous mountainous terrain in East Sikkim district and part of Gangtok region in Sikkim Himalaya. Chandmari area is located within two of its southerly flowing third order sub-basins on the eastern flank of the Gangtok ridge and is an active landslide prone area that has been experiencing subsidence and debris flow. It has a history of land subsidence and land sliding since 1960s, worst being in 1968 and showed reactivations in 1984, 1997, 2007, 2011. Significant subsidence was also observed during recent 2018 and 2019 monsoon periods along with several small surface road-side slumps that blocked transport corridors - the life-line for the strategic international border areas.

The study area falls within the Lesser Himalaya comprising basement rocks of high grade gneisses overlying mica-garnet rich schistose rocks that are weathered to variable depths with irregularly developed soil profiles. The major thrust fault zone [the Main Central Thrust (MCT)], trending NNW-SSE is passing through the area and is traversed by intersecting lineaments trending NE-SW. The drainage patterns observed in the area are structurally controlled and show sub-parallel disposition aligned along faults, lineaments, major fractures/ master joint sets thus adding to the vulnerability for mass-wasting. Superimposition of landslide incidences show that these are concentrated along either 1st or 2nd order drainage courses.

Although previous studies have emphasised that landslides and slope failures are positively correlated with intensity of rainfall received at a given area, yet the threshold limits vary from place to place. A multi-disciplinary team from Amrita Centre for Wireless Networks and Applications, Amrita Vishwa Vidyapeetham, Kerala has already designed, developed and deployed Landslide Early Warning System (LEWS) to monitor the various geotechnical, meteorological and geohydrological parameters in Chandmari area. The research by Amrita group has attempted to establish rainfall thresholds along with the influence of antecedent rainfall in landslide initiation. The proposed threshold equations and study of the effect of antecedent rainfall on landslides have been intended to aid in enhancing the real-time landslide early warning system (R-LEWS) being developed for Sikkim.

Current research in parts of Western Ghats in Kerala has provided encouraging indications that drainage basin-wide approach to understanding the phenomena of multi-hazards including slope failures, mass wasting, and floods, can be considered comprehensively for effective deployment of R-LEWS and application of mitigation measures. In this contribution we have attempted landslide hazard assessment on GIS platform adopting basin-wide approach and considered the five delineated drainage sub-basins that cover the Chandmari and Tatangen and adjoining areas in conjunction with geoscientific ground surveys for evaluating correlation of geofactors and the slope-failure vulnerability as per geomorphometric conditions of the terrain. Initial results and feasibility of natural and human forcing factors and feedback effects as well as strengthening the public resilience for effective implementation of disaster mitigation measures will be presented and discussed.

Variation in the Landslide Analysis from Medium to Large Scale using GIS and Geotechnical approach: a study on Gaj Watershed in Kangra Valley

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The landslide hazard is a sleeping phenomenon that gets nourished by many factors such as continuous draining of the slopes, melting of snow, seepage from man-made water storage, extra overburden on the slopes from the past landslide debris, huge constructions on slopes having low material strength etc. The slope instabilities (landslides zones) from the Gaj watershed were spatially mapped (medium to detailed scale) and correlated with the causal terrain factors in order to develop landslide susceptibility zonation (LSZ) maps. In this process firstly, on a medium scale a landslide inventory was prepared by demarcating 191 landslide sites on the high resolution LISS IV mx satellite data. The terrain causal factors and their sub-classes were assigned weightages either by using subjective judgements (AHP method) or the statistical overlay of the factors with the landslide inventory map (InV and FR method). The differences among the landslide susceptibility maps resulting from subjective (AHP) and objective (InV & FR) rating approach were evaluated. In the next step, the landslide susceptibility zonation (LSZ) on a large scale (1:15,000) was carried out for the most developed and the worst landslide hit area in the Gaj watershed i.e. Dharamshala region (39.5 km^2). A landslide inventory covering 39 landslide locations was prepared and was correlated with the probable causal terrain factors. The factor maps were prepared in ARC GIS and were homogenized at equal grid size. Now, the factor maps and their sub-classes were assigned weightages using the heuristic method i.e. analytical hierarchy process (AHP) and the statistical method i.e. Frequency ratio (FR). Bringing the study from a medium scale towards the larger scale has shown the type of lithological class and category of the steep slopes (with inhabited area) are responsible for the landslides in the region. This study helped to bring out the anthropogenic and the natural factors causing the landslide problems in the Dharamshala region. Now, taking the landslide study from a large scale towards the site-specific slope analysis, one of the major landslide events from the Dharamshala region (Tiralines landslide) was evaluated using the geotechnical analysis of slope material and numerical simulations using finite element method (FEM). The Tiralines landslide was firstly mapped (total station method) at the scale of 1:500 using total station. Apart from this, the slope soil samples were collected for studying in the lab (geotechnical analysis) which revealed their grain size, density, moisture content, permeability and the shear strength (c and Φ) parameters. The material properties (geotechnical) were then used as input in the $Phase^2$ software for carrying out the finite element analysis of the slope sections chosen from the landslide body. The geotechnical lab study revealed that the sandy composition of the slope material with high permeability and low dry density resulted into larger void ratio. This may have led to the development of pore pressure resulting from the prolonged precipitation episode or unplanned drainage systems. The numerical Finite Element method (FEM) used for the slope stability analysis depicted the shear strength reduction factor at which the slope sections are subjected to failure. This study has also shown the application of site-specific landslide analysis which pointed out the specific causes of the slope instability due to the inherent properties of the slope material and effective load on them.

The above discussed study of the Gaj watershed and the Dharamshala region shows the application of conducting landslide analysis from medium to detailed scale and how the results vary in each case.

Impact of Ground Accelerations on Landslide Triggering in Garhwal Himalaya

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The ground accelerations generated by the earthquakes causes landslides and in many cases contribute towards the triggering of landslides at vulnerable sites. The occurrence of earthquakes in landslide-prone areas greatly increases the likelihood that landslides will occur, due to ground shaking alone or shaking-caused dilation of soil materials, which allows rapid infiltration of water. The Garhwal region in Himalayas exhibits frequent occurrence of earthquakes and landslides. In the recent past, the two moderate earthquakes, M6.6 (1999) Chamoli earthquake and M6.5 (1991) Uttarkashi earthquake, have triggered 79 landslides. The analysis has been carried out for 21 earthquake events, M_L 4.0, recorded between 2007 and 2015, by WIHG broadband network in Garhwal Himalaya, for computing Peak Ground accelerations (PGA). The maximum PGA value of 0.21g has been obtained. Although it is far too low as compared to the PGA value of 0.32g for Uttarkashi earthquake, but it is sufficient to trigger a landslide at a vulnerable site. An attempt has been made to evaluate the impact of ground acceleration, using Mohr circle failure criteria, at a vulnerable landslide site with reference to site conditions of slope and road cutting.

Precipitation Intensity –Duration (I-D) based Modelling as an input for Landslide Early Warning System (LEWS)

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Alaknanda river basin located in the Garhwal region of Uttarakhand is characterized by rugged topography and deep gorges running across several hundred kilometres. Every year during the extreme monsoon season from July to September, a large number of landslides are reported from different parts of the basin mainly along the NH-58 highway which runs for 128 km along the Alaknanda river. Frequent landslide occurrences along the highway has apprehended the attention of the disaster management authorities, scientific communities and local citizens as they result in a catastrophe leading to both destruction and casualties at a humongous scale, disrupts the traffic thus affecting the daily livelihood of the locals and also leaves the tourists and pilgrims stranded for hours to days. Taking these factors into view, it is highly desirable to develop a methodology that can contribute in landslide hazard assessment and early warning.

Major landslide activities take place during the monsoon season therefore, it is necessary to understand precipitation as the triggering mechanism and establish rainfall thresholds for landslide initiation. The present research aims to establish intensity- duration (I-D) based rainfall thresholds for landslides forewarning. The intensity- duration based equation is determined by using GPM (Global Precipitation Mission) rainfall data with a spatial resolution of 0.1x0.1 degree and temporal resolution of half hourly and one day. Besides this, landslide event records were obtained from Border Road Organization (BRO) for the years 2017 to 2019. The validation of the equation was carried out for the monsoon months from 1st June to 30th September for the year 2015. The intensity- duration equation showed inverse proportionality between the intensity of rainfall and the continuous duration. The present approach can help in assessing the precipitation intensity and duration in one equation, so that for a known intensity of rain, the duration of precipitation required to cause landslide can be determined. If there is a variable intensity and the precipitation is continuous, the weighted average can be considered to determine the duration, which will eventually give probable time of failure. As the equation is unique to each geological domain, the variability in rocks, soil and structure is assumed to be factored in the analysis. Once the duration and probable time is known, then debris flow model or rock fall model can be carried out to identify potential areas of failure and movement of landslide mass. Therefore, the present model is an attempt that can be integrated in a comprehensive landslide early warning system as envisaged by National Disaster Management Authority (NDMA), in recently published strategy for landslide hazard mitigation.

(Any) Lesson learnt from 2011 Sikkim Earthquake Induced Landslides (?)

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The Northern-Eastern state of India, Sikkim has a very specific and unique place in the tourism map of India. Every year, lakhs of people use to visit the state. To accommodate such floating population in the area, some big towering buildings/hotels have been constructed. But, unfortunately the area is under the threat of many natural disasters such as earthquake, landslide, cloud burst etc. In the year 2011 on 18th September, big 6.8 Mw earthquake rocked the state. Apart from major damage due to earthquake, the region experienced a number of earthquake induced landslides. These landslides were reported as far as ~100 km epicentral distance from the earthquake. Many big human made structures like roads and building were destroyed due to earthquake and landslide incidences. Many small earthquakes are still continuing in the region after this major earthquake. After the 9 years of incidence, Gangtok city and other parts of the state again reconstructed and regained its original shape but unfortunately most of this new construction is either established on the high slope area or refurbished building without considering the geo-technical properties of underlying soil. To know the understanding of people about the natural hazards, a people perception survey was carried out in the Gangtok Municipal Corporation (GMC) area. The preliminary results of people perceptions' data in Gangtok Municipal Corporation (GMC) show that earthquake is most deadly hazard in the region after landslide, soil erosion and hailstorm. Although, the people of Gangtok know about the vulnerability of earthquake induced landslides, but still constructing the high towers in high slope areas without scientific knowledge. So the present paper deal with some case studies in Gangtok city with an open question "*Did we learn (any) Lesson from 2011 Sikkim earthquake induced landslides (?)*".

Landslide Susceptibility Assessment of Munsyari Block, Pithoragarh, Uttrakhand, India

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Landslide risk can be assessed by evaluating geological conditions associated with past events. Frequency Ratio model has been successfully applied as statistical approach for landslide susceptibility assessment in many regions all over the world. In the present study, Munsyari block of district Pithoragarh , Uttarakhand has been selected as a case study to apply the FR model for landslide susceptibility assessment and mapping. For this, landslide inventory map was firstly constructed, landslide locations identified from various sources i.e. GPS and satellite imagery, Remote sensing and GIS techniques were used for the further analysis. These landslide locations were then randomly selected 70% landslide locations (for training process) and 30% landslide locations (for validation process). In this study landslide conditioning factors (slope, aspect, elevation, curvature, land use, geology, soil depth, distance to road, distance to river and rainfall pattern) have been selected for analyzing the spatial relationship with landslide occurrences. Using training dataset, the FR model was then built to assess landslide susceptibility in the study area. This landslide susceptibility assessment can be used as a tool to help identify land areas best suited for development by examining the potential risk of land-sliding and can help in better preparedness for future landslide Hazards in the study area.

Application of Different High Resolution DEMs in Numerical Simulation and Modelling of Selected Landslides in Uttarakhand Himalaya

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Uttarakhand Himalaya encounters a large number of landslides in different regions and mainly along the national highways during the monsoon season. The frequent occurrence of landslides disrupt the life of the local people and cause destruction and casualties at a large scale. Therefore, it is necessary to take relevant mitigation measures to make the landslide affected areas and surroundings less vulnerable to the landslide hazard. In complex rugged terrains, numerical process-based physical models, owing to its objective outputs, are used to predict the runout of rock falls and debris flows. The models are helpful while adopting geotechnical mitigation measures and timely optimization of the limited financial resources available.

Different state-of-the-art methods employing DEMs from different sources and spatial resolutions like ALOS PALSAR, SRTM, Cartosat, TLS and UAV derived, are employed in

an integrated for the first time to acquire data related to landslides and attempt modelling. The TLS is used for acquiring dense point cloud with 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. In Nainital, the technology was demonstrated to assist state government in acquiring authentic information on the extent of landslide in 3-D along with high resolution DEM and surface cover. Pertinently, the entrained release area, calculation domain, calibrated values of the friction and turbulent coefficients as used as basic inputs in the simulation apart from a high resolution DEM. Nnumerically simulated models, employed for prediction of run out path in three dimensions and provide velocity, momentum, height and pressure at Koti, Langsi, Nainital landslides. Geophysical investigations can also help, in compliment, to determine the slip surface and other sub-surface details, which can only be obtained by expensive and time-consuming drilling otherwise, like detection of landslide scarps of substantial dimension e.g. Kunjethi (Kalimath) Landslide, near Ukhimath. These emerging technologies caters to high resolution terrain attributes essential for landslide modelling, designing remedial measures, to evacuate people and also help to simulate and understand the actual cause, process and mechanism of landslides.

Predicting Long Term Stability of a Road cut slope in the Himalaya

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Slope failure and landslides are one of the major problems in Himalayan terrain which is tectonically active zone. Instability of rock masses along cut slopes leads to probability of loss of lives and properties. In the present study, we have analysed the stability aspects of cut slope along Rishikesh-Badrinath road (NH-58), Rishikesh, Uttarakhand. The coordinates of the study area are N30º7′24.19″ and E78º22′51.28″. The topography in the area is rugged with high mountains and moderate slopes. The height of the hill slope is 35m from the road level with an inclination around 70º towards SSW. The upper face of cut slope is covered with colluvial overburden of medium to clayey/silty matrix and vegetation. The rocks at the cut slope were dolomitic limestone with shale bands. Geologically, the study area lies between two thrusts, MBT and Nayar Thrust (NT). The dolomitic limestone and shaly rocks in study area near Shivpuri, Rishikesh belong to Late Proterozoic to Early Cambrian formations (Chaosa, Blaini, Infra-Krol, Krol and Tal formations). The rock mass is exposed along the cut slope and had a geological strength index of 56. Three discontinuity sets (J1 Dipping 60º towards SSW, J2 dipping 55º towards NNW, J3 dipping 50º towards ENE) are present in the area. In the present work, we have assessed the long term stability condition of cut slope through kinematic analysis, geo-mechanical and limit analysis. The results, done for the dry condition depict high chances of planar and wedge failure, if they are not stabilized. Slope mass rating of planar discontinuity at the slope is of Class V, indicating complete instability and SMR rating of wedge failure is of Class II indicating stability at the wedge.

A Framework for Landslide Early Detection (LED) and Early Warning System (LEWS) using Space and Ground Based Inputs

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Coupling of climate, erosion and tectonics has resulted in numerous landslides in Himalayan region, which is one of the most tectonically active regions of the world. The problem of landslides is further accentuated by lack of due attention to this intrinsic relationship in infrastructure development, land use practices and other human activities. The problem has aggravated in an unabated manner in recent times so much that the entire Himalaya across India, Nepal and Bhutan has emerged as the hot spot of landslides on global map. The loss of lives and property can attain alarming proportion as observed during Kedarnath 2013 disaster, which was a combination of GLOF, flash flood, landslides, and bank erosion. The most critical element in a framework for comprehensive landslide management is the appreciation of above factors, their combined role and early detection leading to early warning and a mitigation strategy that is sustainable in future.

Towards above satellite based observation including both optical remote sensing and microwave remote sensing can play a crucial role particularly in the following activities: mapping of active and old landslides and causative parameters; development of spatial models for identification of landslide hazard zones; implementation of deterministic modeling and factor of safety calculation; slope deformation monitoring using DInSAR, PSInSAR, SBAS and GNSS; slope monitoring using terrestrial laser scanner/UAV (which can provide very high resolution image and DEM at very high resolution); sub-surface probing by geophysical techniques; monitoring performance of slope stability measures. Most importantly all of the above can be integrated in a system for both Landslide Early Detection (LED) and Landslide Early Warning (LEWS), wherein the former refers to a situation where landslide process has initiated but catastrophe is yet to take place and in the second case the conditions prevail for landslide to take place.

The LED and LEWS as a part of integrated system could have the following components: 1. Setting up of automated rain gauges and analysis of precipitation data from AWS/ARG and satellite based observation (ISRO/IMD Rapid, GPM); 2. Landslide inventory and preparation of LHZ maps; 3. Establishment of landslide, rainfall threshold relationship and intensity duration relationship (RT and ID) and estimation of landslide probability for different zones; 4. Use rainfall prediction (ISRO/IMD Rapid and global data) and assess the landslide probability; 5. Based on deterministic modelling, factor of safety can be assessed for the same phenomenon; 6. Issue of early warning based on precipitation (satellite and ground), ground based instrument as and where installed and deterministic modelling, if available; 7. Deformation confirmation and monitoring by DInSAR/SBAS/PSINSAR/

GNSS, ground based observations including that by community/stake holders; 8. Use debris flow/rock fall modelling for flow path and run-out estimation; 9. Evacuation/restrict vehicular traffic; and 10. Mechanism to take off warning. A modified methodology can specially be envisaged for earthquake triggered landslides using Newmark model in GIS with geotechnical inputs.

In the present context an attempt is made to assess the steps required to achieve Zero "0" casualty status in the event of landslides as has been achieved for cyclone to a great extent by eastern states of India. As most of the large landslides are due to natural causes, containment or mitigation of the same is more time and cost effective than control majors. It is very interesting to note that in the Indian Himalaya, a large number of institutions are already pursuing studies in some of the above mentioned areas and have taken steps to install systems that can contribute immensely in developing LED and LEWS. The space based solutions as mentioned can contribute in developing LED and LEWS across large tracts of Himalaya in a scalable manner starting from regional to individual slope monitoring and in situations where no or little data exists to situations where detailed ground-based information is available, thereby justifying universal applicability.

Structural Damage Zones and Slope Stability: A case study from Mandakini Valley, Uttarakhand (India)

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Mapping of structural damage zones along the Mandakini River from Sonparyag to Rudraparyag, approximately 76 km have been mapped. This study presents the relationship between structural damage zones and slope stability. Different kind of shear zone rocks/ damage zone rocks; mylonitic gneiss, mylonitic augen gneiss, ultramylonite, protomylonite and phyllonite are present. Major tectonic structures like Munsiari Thrust (MT) or Main Central Thrust-1 (MCT-1) passes near the Kund village, Tilwara Thrust traverses from Tilwara village and some outcrop scale shear zones and damage zones are marked on the map. These thrust zones or damage zones are more prone for landslides. Damage zones areas are more unstable and vulnerable for landslides. To confirm our field observation, slope kinematics analysis for type of failure and slope mass rating (SMR) are performed. Field observations based on damage zones and SMR values show a good relationship in the area.

Landslides in Sikkim Himalaya - Study at IIT Kharagpur

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The findings from the past and the ongoing landslide studies undertaken by the Department of Civil Engineering, IIT Kharagpur mainly on the eastern part of India including the Himalayan region have been reviewed. The ongoing (2017-2021) Indo-Norway project on landslides sponsored by the Ministry of Earth Sciences (MoES), New Delhi involves INSAR monitoring of landslides in Sikkim along the two transects, ground monitoring using LIDAR scanner & Quadcopter, numerical study of the landslides, development of hazard zonations along the two corridors, and study of possible mitigation measures. The project is executed by NGU and NGI of Norway, and WIHG & IITKgp. from India. Based on the study done so far, several landslides in the study area have been selected for in depth study to evaluate their potential to cause major damages and disruptions. One of these landslides is presented here.

Landslide Susceptibility Modelling using Weight of Evidence method in West Sikkim district of Sikkim Himalaya

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Sikkim Himalaya is well known for active mass movements. Different mass movement features including debris flows, debris slides, rock slides and soil slides in this area are regular phenomenon. Detection of vulnerable areas is the priority of disaster management and an important foundation for promoting healthy human occupation and the growth of infrastructure in hazardous areas for slope instability. There are numerous methods of landslide mapping but in this study, the weight of evidence (wofe) method was used to create a map of landslides that are hazardous. Present study was carried out in the West Sikkim district of Sikkim. LISS 4 with 5.8m resolution data was used. Different factors causing landslides such as slope, aspect, rainfall, lithology, elevation, road buffer, drainage buffer, structures, LU / LC and standardized vegetation difference index (NDVI) were analyzed to determine the contribution of each factor for triggering the landslide. The modeling will be executed using a Geographical Information System (GIS) and a statistical approach. Landslide inducing factors were measured and weighted using the wofe method for creating a map of landslide-prone areas. 70 percent of the total landslides were taken as training sites to carry out the present study and the remaining 30 percent of the landslides were taken as test sites. On training and validation sites, the overlay method supported by the receiver operating characteristic (ROC) and the area under curve (AUC) was applied to assess the accuracy that was more than 70%.

Bhatwari and Raithal mountain villages of Garhwal Himalaya creeping rapidly due to landslide: Evidence from GPS, Field and InSAR studies

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GPS has been installed for monitoring landslides along the Main Central Thrust (MCT) zone of Garhwal Himalaya where landslides are more and causes severe damages for the infrastructures developed in the narrow river valley of the mountain state. Here, we report on two cases of continuously recording of slow moving potential landslides from the Garhwal Himalaya using GPS measurements. Two adjacent sites at Bhatwari (BHTW) and Raithal (RATH) villages in the landslide prone MCT zone of Uttarkashi region, record time varying rapid eastward movement in the downhill slope. The site RATH located at the crown is moving at slower rate than the site BHTW in the toe, since 2006. The relative motion between these two sites seems to be increasing with time and it is in harmony with the ground deformation features. The point based geodetic motions at BHTW and RATH, are also substantiated with Interferometric Synthetic Aperture Radar (InSAR) analysis. These results together with the high resolution field surveys using RTK (real-time kinematic) and detailed field investigations suggest that BHTW and RATH sites, located on a gently sloping spur size of ~2×2 km^2 exhibit a creep motion towards east since 2006 at a rate of 12 mm/year, which increased to 22 mm/year in 2016. However, it is not clear whether the measured movements in this region may direct to catastrophic landslides during seasonal monsoon or extreme event or during small or large earthquake. Hence, detailed monitoring of the two identified regions is warranted to avoid the potential secondary effects such as the damming of Bhagirathi river and subsequent floods.

Landslide hazard assessment using frequency ratio: A case study of southwestern part of Chamba District, Himachal Pradesh, India

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The southwestern part of Chamba district is evidence of several natural hazards attributed to frequent seismicity, heavy rainfall and fragile rocky landforms. Landslides are one of the most recurring dangers with destroying impacts on economy and society of the region. Present study aims to develop landslide inventory and hazard zones of the southern part of Chamba district, which comprises of two important road networks, National Highway 154A and State Highway 28. Interpretation of satellite images (Cartosat 2D, LISSIV, and Google earth) along with ground truth survey helped in the development of landslide inventory. It was observed that landslide distribution in study area was stimulated by causative factors like slope gradient, aspect, geology, soil properties, geomorphology, rainfall, land use/land cover, lineament density, drainage density, relative relief, and curvature. Analysis of these

factors reveals that rainfall played significant role in landslide occurrences followed by geology, lineament density, drainage density, land use and land cover. These results are obtained using frequency ratio method to produce landslide hazard zonation (LHZ) map. Accuracy of landslide hazard map was tested through successive rate curve method showing 87.17% accuracy.

Slope Stability investigations along the Mansa Devi hill-bypass (MDHB) Road, Haridwar, Uttarakhand, India

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Slope instability is one of the most serious geological hazards that can occur both in soil and rocks and causes substantial economic and environmental losses throughout the world. The causes of slope instability in an area can be due to anthropogenic factors as well as due to natural factors like changes in groundwater as results of excessive rainfall, weathering, frost action, tectonic forces, geological processes, joint patterns, slope geometry, weaker slope material, etc. Both these factors act together on the slopes and most of the time, it became difficult to assess the prominent factor causing instability in an area. Thus, an integrated study of the geological, geomorphological and geotechnical parameters is necessary in order to understand the causes of slope instability in an area. It also helps to design the required mitigation measures.

In the Indian terrain, the Himalaya is one of the hotspots of landslide and hence massive loss of lives and infrastructure along with disruption to transport, water supply and telecommunication are incurred every year, mainly during monsoon season. The unstable areas in the Himalaya are widely spread and located in different tectonic zones i.e. Sub Himalaya, Lesser Himalaya, Central Himalaya, and Tethyan Himalaya and thus varied in their geological, geomorphological and meteorological conditions. In the present study, an attempt has been made to assess the causes of instability along the Mansa Devi Hill Bypass (MDHB) road located in the Sub-Himalaya. Geologically it is composed of alternate sequences of sandstone and mudstone beds. Detailed geological, geotechnical and ground penetration radar (GPR) studies were carried out to study the behavior of slope forming material and to understand sub-surface conditions along the MDHB road. The laboratory tests were carried out in order to evaluate the geo-mechanical characterization of soil and rock. Kinematic and slope stability analyses were also performed and the factor of safety was determined using Software Slide 4.0 based on limit equilibrium method.

The results reveal that soil comprising the slope has high permeability and lower strength values. It is mainly sandy in nature with an average value of cohesion and friction angle are 0.15 MPa and 33° respectively. The infiltration rate of water in this sandy soil is generally

rapid which allows a fast flow of water into the deeper horizons. The mudstone is nondurable and contains a considerable amount of expanded clay minerals which have tendency to expand with the action of water, thus weathers easily and facilitates instability at a shallower depth. It has also been confirmed in the GPR survey that the road is unstable particularly on those spots where road either lying over mudstone beds or over thick non-cohesive sandy soil. The same results have been attributed in slope stability analysis in which factor of safety is < 1 where the MDHB road is either constructed over mudstone beds or over the sandy soil.

Role of Geological Investigation to Decipher Vulnerable Landslides between Saknidhar and Devprayag area along National Highway 58, Uttarakhand, India

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As part of an unstable tectonic system, the Himalaya is facing different natural and man-made disasters. Likewise, Uttarakhand's hilly terrain experiences various natural disasters. Landslide, one of the most common disasters during the monsoon season, leads to loss of life, property and hampering the transportation and communication system. Present study aims to investigate vulnerable landslides zones and their causative factors from Saknidhar to Devprayag, Uttarakhand along the National Highway (NH) 58. This highway is the lifeline for the residents of Tehri, Uttarkashi, Chamoli, Rudraprayag and Pauri Garhwal districts. Satellite imageries, toposheet (53J/12) and GPS on GIS platform were used to analyse the data. Large scale geological mapping was carried out to identify the slope instability. Sandstone and quartzite of the Chakrata Formation and phyllites of the Chandpur Formation display different types of discontinuities and shuttering of rocks. Debris slide, rock fall and creeping are most prominent mass movement phenomena observed in the study area. Present road widening under Char Dham Yojana project along NH 58 necessitates simultaneous suitable mitigation and treatment of potential landslide zones. There are 12 vulnerable landslides observed in and around the study area. Based on field and satellite based information, landslide inventory map was prepared. The paper discusses about the causative factors of triggering of landslide such as precipitation, higher density of fracture, joints, steep slopes, brittle-ductile shearing zone toe erosion, and unplanned construction work. Bioengineering, retaining wall, wire mesh, anchoring, rock bolting, shortcrete and culvert pipe are the suggested as mitigation measures which will be very helpful for slope stability and smooth operation of vehicular traffic in future.

Landslide Hazard Assessment Using High-Resolution Space Data for Kullu District, Himachal Pradesh, India

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The whole of the Indian subcontinent is susceptible to natural disasters of various kinds. The records over the years indicate that disasters have been on the increase both in terms of frequency and severity. The State of Himachal Pradesh which forms a part of the North-western Himalaya is environmentally fragile and ecologically vulnerable. Occurrence of natural hazards emanating from the effects of climatological variations are a matter of immediate concern to the state, as every year the state experiences the fury of nature in various forms-like cloudbursts, flash floods, landslides, earthquake, snow avalanches and droughts etc. The fragile ecology of the mountain state coupled with large variations in physio-climatic conditions has rendered it vulnerable to the vagaries of climate and natural disasters. The study area in Kullu district being the mountainous terrain, the district is highly prone for disasters of different nature and has been affected by different disasters of geological, water and climate origin like earthquakes, landslides, floods, snow avalanches, Glacier Lake Outbursts Floods (GLOFs) etc. Landslide is one of the most common natural hazard prevalent in the study area. As the study area is characterised by the presence of highly fractured and jointed metamorphites as a result of which the mass movements along the hill slopes is a common phenomena.

Based on the satellite data analysis, an inventory of existing landslides has been prepared in the entire Kullu district covering the study area and their correlation has been done with the other parameters like geology, geomorpholiogical features of the area illustrating which are more prone for landslides. Using satellite data, an attempt has been made to describe the area in terms of erosion intensity based on geology, drainage density, geology, geomorphology, slope and the land use land cover based on which the entire study area has been divided into four different zones describing the characteristics of each zone and defining its proneness and the vulnerability based on the risk elements involved.

Considering the proneness of each zone to landslide hazards in Kullu district, overall vulnerability assessed in each zone is reverse based on the risk elements, developmental activities, inhabited areas etc. The Zone-IV where the proneness is comparatively low, but since the risk elements like thickly populated areas, very high range of developmental activities, highly fertile land, dense road network, tourism activities are very high in this zone, thus if any landslide/mass movement occur in this zone, the vulnerability increase manifold and hence the vulnerability of Zone IV is very high. On the contrary Zone I which has very high proneness for the landslides, the vulnerability in terms of the above mentioned risk elements is next in severity to zone-IV and has been termed as highly vulnerable as far as the landslide hazard risk assessment in Kullu district is concerned. The other two zone i.e

Zone II and III which have moderate to high proneness for the landslides, but because of the location of these zones, the risk elements are scarce and isolated in nature, most of the area is hilly where developmental activities are very less, with the result the vulnerability of these two zones has been termed as moderate as far as the landslide hazard risk assessment in the Kullu district is concerned.

Building resilience and reducing the risk by way of having appropriate preparedness measures by adopting effective warning systems, increasing community awareness and preparedness, and sustainable land use planning would not only help in minimising the hazard impact but also will reduce the post disaster effects.

Landslide studies between Devprayag and Srinagar along National Highway - 7, Lesser Garhwal Himalaya

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Landslides are very common geological hazards which occurred in Himalayan region mostly during monsoon season. It may be caused either due to natural factors such as rainfall, lithology, geomorphology, seismicity, mountain slope, geological structures etc. and anthropogenic factors such as road widening, blasting, deforestation and construction of houses etc. The present studies of landslides have been carried out along the National Highway-7 from Devprayag (N 30^0 08'40” & E 78^{0}35'44”) to Srinagar (N 30^0 13'16” & E 78^0 47'26”). The detail geological and structural mapping has been done on 1:10,000 scale. Phyllite is the dominant rock along the road and at some places quartzite and slate rocks also present. During the fieldwork sixteen landslides (L_1 to L_{16}) have been observed along the road section. Maximum landslides are present in phyllite. These landslides are debris slides (L_1, L_2, L_5, L_6, L_{11}, L_{12}, L_{13}, L_{16}), rock fall (L_7, L_8), debris cum rock fall (L_9, L_{10}, L_{14}), soil creep (L_3, L_4, L_{11}) and subsidence (L_1, L_{15}) types. At two places kinematic analysis of slope failure have been done which shows wedge failure. These landslides (L_1 to L_{16}) affect National Highway, houses (L_1, L_2, L_4, L_{15}) and school (L_3). Active landslide, potential landslide and safe zone are also marked on the map. After the detailed investigation nine damaged zones have been identified along the road. During the fieldwork causes of landslides have been observed. Some safety measures of these landslides are also suggested such as netting, rock bolting, retaining wall, surface drainage and plantation etc. on damaged surface. This study can help reducing the risk of human life, betterment of Char Dham yatra and may also contribute to the ongoing constructions work in the area.

Regional-Scale Landslide Susceptibility Assessment of the Uttarakhand Himalaya

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Uttarakhand is known for the occurrence of higher numbers of geohazards including landslides. It has been reported that the frequency and magnitudes of landslides in Uttarakhand increasing exponentially. This increase is mainly because of the increasing population pressure on the limited land resources, thereby increasing the slope instability in the region mainly because of the construction of dams, roads, tunnels, bridges, hydropower-projects etc. Thus, there is need for landslide susceptibility assessment of the region. For the present work, regional-scale landslide susceptibility assessment of Uttarkhand covering an area of ~ 54000 km^2 has been carried out using a bivariate statistical method. In the entire area, 3303 active landslides were mapped. These range in size from ~ 25 m^2 to ~ 2.5 km^2. Ten possible causative factors of landslides viz. lithology, slope angle & aspect, elevation, curvature-plan, curvature-profile, distance to drainage, road & thrusts, land use and land cover were taken into consideration for the preparation of landslide susceptibility assessment. The thematic layer for each causative factor was prepared using the primary as well as the secondary data. 70% of the total landslides were randomly selected and were used for the preparation of the susceptibility map, whereas the remaining 30% landslides were used for validating the model.

It has been observed that 28% of the study area falls under high and very high susceptible zones followed by 27% in moderate and 45% in low and very low susceptible zones. The high and very high susceptible zones are mainly concentrated along the strike of the MCT. It has been noted that the susceptibility model has an area under curve (AUC) values is 0.92 for the success rate curve and 0.90 for the prediction rate curve.

Comparing Earthquake and Rainfall-induced Landslide Inventories in the Himalayan region

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This paper gives an overview of recent research on generating landslide inventories of triggering events by earthquake and extreme rainfall in the Himalayan context, and how these influence subsequent landslide susceptibility, hazard and risk assessment. Within a collaboration project between between ITC, GSI and NRSC , a number of techniques were developed for landslide inventory mapping, ranging from using Object Based Image Analysis, to the use of available records and collaborative mapping using Google Earth Images for the generation of event-based landslide inventories. The completeness of landslide inventories and its spatial and thematic accuracy are discussed in relation to the effect they have on the evaluation of landslide susceptibility and hazard assessment. Also a collaboration with the USGS is discussed for the generation of a web-based portal of earthquake-induced landslide inventories for major historical earthquakes. It is very important to collect as many of these event-based inventories in order to better correlate them with the specific characteristics of the earthquake that triggered them and the terrain conditions, in order to develop methods for earthquake-induced landslide hazard. Event-based landslide inventories are used to estimate the relation between temporal probability, landslide density and landslide size distribution. Examples are given of the work that was carried out after the 2015 Gorkha earthquake in Nepal. Object Based Image Analysis (OBIA) combined with machine learning methods were used to generate landslide inventories from before, during and after the earthquake, and the characteristics of earthquake-induced landslide inventories were compared with rainfall-induced landslide inventories. The contributing factors related to topography, geological and land cover were analyzed for both inventories for different landslide types and sizes. In order to develop rainfall thresholds as a basis for Landslide Early Warning a study was carried out in the Rasuwa district of Nepal, using a combination of satellite based rainfall estimates, rainfall station data, and physically-based modelling of soil water conditions and slope stability. Also multi-hazard relationships (earthquake-landslides-flooding-debrisflows) were modelled using a physically-based model in comparable environments affected by earthquakes, in order to analyze the post-earthquake changes in landslide hazard intensity.

Rockslide Monitoring and Early Warning in Norway

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Large rockslides or rock avalanches are rare with around three events occurring in Norway each Century. While infrequent the number of fatalities of such events have been high, primarily from tsunamis created in the fjords or lakes. In low seismic zones rock avalanches are usually pre-cursed by fracture opening and acceleration prior to failure; this has been established both at historical events in Norway and internationally.

The Norwegian Water Resources and Energy Directorate (NVE), is managing the risk of large rockslides in Norway. The mapping of unstable rock slopes is done by Geological Survey of Norway (NGU) and risk classified by hazard score (probability) and consequence in terms of potential loss of human lives. After the risk classification, NVE is responsible for following up the unstable rock slopes. Rockslides classified with a high risk (high probability and large consequences) are instrumented and monitored 24/7 and medium risk rockslides are monitored periodically.

The primary purpose of the mapping and monitoring of large rock instabilities is to prevent the loss of life from rock avalanches. The Norwegian building codes allows for construction and development in the tsunami hazard zones, on the condition that the monitoring systems allows for safe evacuation of inhabitants prior to failure, with a warning time no less than 72 hours. A requirement is independent and redundant instrumentation in the high-risk objects and redundancy in the real time communication.

Today seven high-risk objects are monitored with in situ instrumentation providing high quality measurements of fracture opening (extensometers and lasers) or general movement like GPS or total station etc. In some cases, measurements of movement in the sliding plane is measured by borehole instruments. Continuous monitoring by ground based InSAR systems are used at some high-risk objects. Rock slopes classified with medium risk are monitored less intensively and mainly by InSAR from Sentinel 1 satellites towards corner reflectors placed inside the instabilities and automatic processing of PSI InSAR data. Periodic measurements by GPS or extensometers may also be used for medium risk objects. In case of increased movement of a medium risk object, additional instrumentation will be installed, and the object could be reclassified as a high-risk object if the movement remain large.

NVE is responsible for issuing hazard levels, color-coded from green to red, for each object. The hazard level is based primarily on movements measured in the rockslides. The municipalities are responsibility for using the hazard zones in the areal planning and for the early warning systems. In case of orange hazard level, vulnerable buildings (like kindergartens) are evacuated and in case of red hazard level, all inhabitants of an area are evacuated. The police are responsible for handling evacuations.

Back analysis of Shear Strength Parameters of a Large Rock Slide in Sikkim Himalaya

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Both earthquake and rainfall-induced landslides are quite common in the Eastern Himalayan State of Sikkim. Massive landslides killing tens of thousands of people with catastrophic damages have occurred in Sikkim, which shares common borders with Tibet, Nepal, and Bhutan. Under a joint research co-operation programme between India and Norway (INDNOR), landslide investigations were performed in Northern Sikkim where a massive rock slide called the 'Dzongu landslide' was investigated near the town of Mangan. This huge landslide occurred on the 13th of August 2016 when several million cubic meters of rock mass failed and blocked a tributary of the river Teesta and caused damage to infrastructures in a nearby village. In this presentation, back analysis of the shear strength parameters of this large rock slide is performed to gain a better understanding of its behaviour which led to its failure. Although some early signs of instability could be seen through satellite images in 2006, it is believed that the Sikkim earthquake of magnitude Mw 6.9 on the 18^{th} of September 2011 aggravated the situation which over a period of time reduced the shear strength of the rock mass due to increase in pore water pressure in the slope. Such instability assessments of vulnerable slopes are warranted so that mitigation strategies, such as tunneling, can be planned to bypass major landslides along some critical highways in the Himalaya.

Design of Stabilization Measures for a Large Rock Slope in Bhutan Himalaya

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Several large hydropower projects are under construction in Bhutan which has a very large potential for utilizing its water resources through construction of 'run of the river schemes' for producing electricity. In one of the important hydropower projects along the river Punatsangchhu in Bhutan, a large rock slope along the right bank of the dam axis has become unstable and has been creeping over a period of time. This creep of the slope has caused the whole project to be delayed as the construction of the dam cannot be started before the slope has stabilized to an acceptable level. This presentation describes the monitoring of the slope through ground based INSAR (Synthetic Aperture Radar) and discusses the proposed mitigation strategy to arrest the slope to an acceptable level. The major instability of the slope is controlled by two sliding planes which have been revealed through borehole investigations and inclinometer readings. These readings have been correlated with the surface movement of the slope. Back calculations have been performed for estimating the normal and shear stresses on the sliding planes. Different scenarios for stabilization of the right bank have been suggested. These include a) drainage with long cable anchors b) drainage with long and stiff piles c) drainage with combination of piles and anchors. The pros and cons of each of these scenarios are described in this presentation.

Geomorphological assessment of active tectonics in the Barak River Basin of Western Hills of Manipur, using GIS techniques

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Tectonic geomorphology is considered as an important field of study because the results of regional neo-tectonic studies are essential for evaluation of natural hazards, land use development and management in populated areas. The geomorphic indices act as important indicators in the studies of tectonic geomorphology which are capable of deciphering landform responses to active deformation processes and have been widely used as a reconnaissance tool to demarcate areas which have suffered active neo-tectonics. In regions with active tectonics, the drainage pattern response well to active processes such as folding and faulting which contribute to accelerated river incision, basin asymmetries, drainage geometry and complexity and deflections in river courses. Barak river basin lies in the western hills of Manipur which is a part of the young fold mountain belts of Indo Myanmar range (IMR). The study area has high structural complexity and are seismicity and lithologically unstable consisting of tertiary sedimentary rocks. Landslides are common, causing several social and economic problems. In order to evaluate and understand the tectonic activity of the study area, the basin was divided into seven sub-basins. Geomorphic indices such as linear, areal and relief parameters, Hypsometric integral (HI) and Valley floor width to valley floor height (Vf) ratio have been analyzed for each basin using GIS techniques. The analyzed results have been compiled and expressed by applying the concept of relative active tectonic index (Iat) which were classified into four classes such as relatively low, moderate, high and very high tectonic activity with S/n values >2.5, 2-2.5, 1.5-2 and 1-1.5, respectively and it showed that there is relatively high to very high tectonic activity taking place in the study area. The earthquake and landslide data plotted for the study area are found to be consistent with the result indicated by the relative active tectonic index (Iat). It has been inferred that the geomorphic parameters computed using GIS techniques proved to be a competent tool in the assessment of tectonic activity in the Barak river basin which can be further used in the study of hazards like landslide and earthquake in the basin.

Developing Simple Rules for Landslide Hazard Mitigation

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I present three main aspects of my cross-disciplinary research, arguing against a set of assumptions within the field of disaster risk reduction (DRR) with an overall focus on improving landslide risk mitigation efforts.

There is an assumption that the more technologically advanced, scientifically informed and endowedwith resources a country is, the less the country and its population may suffer from the effects of natural disasters and their resulting impacts. Furthermore, the assumption that there can be 'universally applicable rules' in the context of DRR is challenged. To address these assumptions, I have undertaken novel fieldwork research encompassing and culminating in a comparative case study between two countries (Nepal and New Zealand) that are severely impacted by landslides. I will present these research findings at the International Workshop.

While developed and developing countries may be prone to similar physical disasters, the degree of impact of the events vary extensively. Nepal and New Zealand have in recent years suffered a catastrophic sequence of earthquakes and related natural hazards that were triggered by earthquakes, aftershocks and tremors. Primary hazards such as violent ground shaking and surface rupture as well as secondary hazards such as landsliding, liquefaction, flooding, and changes in river and groundwater flow pose major risks to life and infrastructure (Datta et al, 2018, 11; Orchiston et al, 2018, 389-90). Ground rupture and damage has been responsible for severely impacting transportation of aid, goods and services, and emergency response during the aftermath of disasters, especially to outlying villages and communities.

Landslides are arguably only classified as hazardous when people and the built environment are adversely affected. By contrast, current geological practices for landslide studies almost exclusively take into consideration geo-spatial and temporal elements when attempting to develop strategies for landslide hazard mitigation. However, for mitigation efforts to be effective, some current practices require adaptation, while some approaches to landslide risk mitigation require an overhaul. My research aims to develop simple rules for landslide hazard mitigation that are effective and practical for people to use when faced with impending danger from landslides. The focus on simplification stems from current forms of landslide data remaining in its primary format of technical knowledge without anyone apart from specialists in the field understanding and utilizing the knowledge. Other experts such as civil defence and emergency management, governmental representatives, NGO's and other relief response operators, among others, could benefit substantially from relevant knowledge before, during and after disasters. Moreover, in order for scientific and technical knowledge be put to use for the benefit of susceptible to landslide communities and vulnerable populations, some knowledge needs to be produced with due consideration for end users. I examine the challenges associated with acquiring and using scientific knowledge (like landslide databases) during and after major disasters.

Computer Vision and InSAR based monitoring and analysing the effect of climate change on landslide stability and Glacial retreat

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Climate is the long-term average state of atmospheric physical characteristics. In the last century, the average global surface temperature has been continuously increasing, which shows a consistent warming trend worldwide. Climate changes reflect variations within the Earth's atmosphere, processes in other parts of the Earth such as, oceans and ice caps, and the impact of human activity. Geo-hazards activities such as landslides, glacier movement and snow avalanche have significant impacts on life, livelihood and property in the mountain regions. Himachal Pradesh is prone to a number of natural hazards due to its fragile geological conditions, steep terrain, vulnerable ecosystem, great elevation differences, and variable climatic conditions. Landslides, ice slides, and Glacial Lakes Outburst Floods (GLOF) are all remarkable geo-hazards affected by the climate change. In this study, effect of climate change in landslide has been explored. Moreover, monitoring the surface deformation of the mountain slopes, basic information to understand these geo-hazards, and make risk mitigation have also been attempted. For monitoring the earth surface, Synthetic Aperture Radar (SAR) tool has been utilized. By analysing and processing the remote sensing data of spatial and temporal features of past events, we can predict any disaster in the hilly areas. For this study, we have considered the state, Himachal Pardesh (Mandi-Kullu - Rohtang pass).

Air blasts caused by rock slope failures, what did we learn from the Yumthang 2015 rock avalanche?

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In 2015 a destructive rock avalanche occurred in lower parts of the Yumthang valley in the Sikkim Himalayas (India), interrupting the trans-Himalayan highway connecting India with China and destroying a mountain forest in a powerful blast. The rock avalanche ($12x10^6$ m^3) struck sometime between March 7 and 11, 2015. Its deposit lies over at least two older rock avalanche deposits. In this contribution we back-analyze the airblast destroying the mountain forest and airblasts documented around the world. We determine the conditions of the Yumthang valley rock slope failure and compare those to a data set of a large slope collapses around to decipher the conditions which should be met to trigger a destructive airblasts. Based on those data we establish a semi-empirical relationship linking the potential energy in a collapse with and the area affected by the related airblast. This analysis shows that a large slope collapse falling or jumping over a significant elevation drop (~hundreds of meters), results in a sudden release of energy comparable to the largest bomb used and efficient comminution of rocks. These result in a violent displacement of air. Average wind speeds of airblasts following rock slope failures can be in the order of severe storms.

Engineering Geological Investigation for Landslide Hazard Assessment Along Rudraprayag-Sonprayag Road Sector in the Mandakini Valley

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Landslides are one of the natural disasters that are responsible for huge social and economic losses for mountain populations in terms of human lives, infrastructures and forest wealth. In recent years, assessment of landslide susceptibility in the form of hazard zonation has been attempted in a wide environments and using diverse approaches. The different methodologies developed are influenced by the scale of analysis, the availability of input data, and the required details of the hazard map. The hazard zonation maps on 1:50,000 or

1:25,000 scale are useful to delineate the broad landslide hazard zones; however, large scale maps are required for better understanding of slope instability of a terrain. This requires a detailed survey and mapping of existing and potential landslide slopes.

The road sector from Rishikesh to Kedarnath is having many landslide prone zones due to the geological formation, steep slopes, highly dissected topography, seismically active zone and high rainfall. The consequences and the disaster caused by the debris flow and floods during June, 2013 in the Mandakini valley still can be seen in the area. For constructing a safe built environment, the landslide potential areas should be identified and studied. Keeping this in view a study was carried to assess the slope stability along Rudraprayag-Sonprayag road sector in the Mandakini valley and prepare a landslide hazard map by collecting all possible geotechnical and engineering geological parameters under the DST Network Project.

The tasks involved in the present study was field reconnaissance survey to assess the landslide problems in the area; field investigations to collect engineering geological data and collection of rock and soil samples; laboratory investigation for determination of geotechnical parameters of rocks/soils; preparation of geotechnical database; slope stability assessment based on geological & geotechnical inputs; selection of a few landslide slopes and slope stability analysis; large scale landslide potential map of the road sector. The 80 km road stretch was divided into four sectors for hazard assessment. Sixty slopes along the road were studied and stability assessment was carried. There are various types of landslides present in the study area involving planar and wedge failures, debris slide, rotational slide and subsidence. Detailed field surveys were conducted and relevant data were collected from the selected slopes. Evaluation of stability assessment mainly involved Geological Strength Index (GSI), Rock Mass rating (RMR) and Slope Mass Rating (SMR) techniques. Based on the evaluation of slope stability landslide hazard maps of the four sectors were prepared. Further a few most vulnerable landslide slopes were studied in detail and stability analysis was carried out using numerical modeling. Numerical modeling is a unique approach for slope stability analysis as it encompasses slope geometry, layering of strata, different material properties (elastic and plastic state), and different constitutive models which result into reliable quantitative term, factor of safety of the slope.

The present study provides a detail approach for engineering geological and geotechnical data collection for landslide hazard assessment and the method used for stability assessment. The results of the study will help in evaluating the potential landslide hazards for planning and management of mitigation measures.

Geological and Geotechnical Studies of Vulnerable Slopes along National Highway- 58 (NH-58) Srinagar, Uttarakhand, India

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The failure of rock slopes along the roads in fragile belt of Himalaya is a very common and a critical geological problem. Landslides that happened after Uttarakhand floods in June, 2013 have been creating problems on the strategic National Highway- 58 (NH-58). NH-58 is the main route for well-known pilgrimage sites such as Badrinath, Kedarnath and Sri Hemkunt Sahib which keep the road extremely busy. However, there is also an ever-increasing demand of land for urban development and mega projects such as ongoing railway project from Rishikesh to Badrinath making inhabitants to adapt and survive at dangerous slope margins. In a view of huge societal importance of the problem, landslides in the study area poses serious threat to ongoing traffic and all activities that are related to social and economic well being of Kumaon and Garhwal Himalayas which are dependent on the established road and highway network. All the vulnerable slopes needed to be stabilised through various engineering and bioengineering means in order to protect the living standard of hill people against the increased rate of slope degradation. The area experiences landslides every year and such problems are reported in huge numbers due to geodynamic nature of Himalayan region. In the present study stability analysis of the of road cut slopes along the Alaknanda valley of Dudatoli and Garhwal Group between Srinagar and Rudraprayag on National Highway-58, Uttarakhand has been carried out. Geological and geotechnical methods have been employed to understand the behaviour of slopes. Kinematic analysis has been performed on the slopes to check possible failure modes. In order to check the quality of rock mass along the NH-58, various rock mass characterisation methods such as Geological Strength Index (GSI), Rock Mass Rating (RMR), Slope Mass Rating (SMR) and Continuous Slope Mass Rating (CoSMR) have been employed. Unstable and stable slopes in the study area have been identified and characterized based on SMR and CoSMR.

Landslide Hazard, Risk and Vulnerability Assessment (HRVA) for the hilly township of Mussoorie, Garhwal Himalaya

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Landslide is one of the most destructive natural hazard in the tectonically and geodynamically active mountainous terrain. It is caused mainly by a combination of natural and man-made factors. It becomes hazardous when it interfaces with any human activities. Many of the landslides particularly in the uninhabited mountainous terrain are unreported. In an inhabited area, the loss due to the landslide is increasing exponentially, mainly due to changing climatic scenarios. Therefore there is an urgent need to assess the landslide hazard,

risk and vulnerability assessment (HRVA) of the area and it is also one of the prerequisites for disaster management. In the present study, landslide HRVA for the Mussoorie township located between longitude 77°59'59"E & 78°07'46"E and latitude 30°25'58"N & 30°29'08"N has been carried out. The area constitutes eleven municipal wards, covering an area of ~18 km2. It has a total population of ~30,000, besides numerous floating population. Geologically, the area lies in the Lesser Himalaya and dominantly constitutes dolomitic limestone belonging to the Krol Formation.

In order to prepare the landslide susceptibility map forty-two active landslides present part of the area were mapped. These are mainly distributed in south and southwest portion of the study area. Bivariate statistical method using Yule Coefficient was applied for the preparation of the landslide susceptibility map. It has been noted that ~15% area lies in very high and high susceptible zones, ~31% in moderate and ~54% in low and very low susceptible zones. The low and very low susceptible zones are mainly located towards the north facing slopes, possibly because of the less physical weathering and low heat insolation.

All the elements at risk such as buildings, forest, roads, sewerage, and crop land exposing within 200 m of each landslide were taken into consideration for the preparation of landslide vulnerability map. It has been observed that ~40% of the area is very high and high vulnerable, ~11% moderate, and ~49% is low and very low vulnerable. High and very high vulnerable zones are located in west and central portion mainly because of higher population and more anthropogenic activities.

Finally, hazard and vulnerability maps were overlaid to prepare a risk map which indicates that ~21% of the area is very high and high risk, ~33% is moderate, and ~45% is low and very low risk. The results indicate that central and western portions are more prone to landslide risk because these areas are highly populated. The outcomes of this study may be useful for further development and planning purpose.

Mapping the neighbourhood in Uttarakhand (MANU): Disaster of June 2013

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On 16th and 17th June, 2013, high intensity rainfall (> 400mm) in different parts of the state of Uttarakhand caused devastating flash floods and triggered widespread landsides incurring heavy losses to the infrastructure, agricultural fields, human and animal lives, roads and widespread destruction of natural resources. Department of S&T, Govt of India initiated a unique program to understand the underlying causes of this disaster and initiated a program called as “Mapping the Neighbourhood in Uttarakhand (MANU)” The program had a mandate to map the disaster elements like landslide, damages in building, bridges, culverts and road in all the major river valleys of Uttarakhand.

Observations in the Bhagirathi river valley in Garhwal Himalaya showed that as a result of the event a total number of 1034 landslides got reactivated/initiated; bridges and culverts were found to be damaged at 44 locations and a total 717 buildings were found partially or totally damaged. Riverbank erosion along Bhagirathi and Bhilangna occurred mainly above the town of Uttarkahsi at 170 locations. Roads in river valleys mostly follow the course of the rivers and run 20-200 m above the channel are seen damaged at 494 places and the damage is almost uniformly distributed and is controlled by landslides, riverbank erosion and overland flow.

The longitudinal river profile of the river has two major zones. Zone I that lies above Uttarkahsi has channel gradient ~11.8 degrees, is characterized by the bedload dominant sediment load and steeper tributaries. The lower part of this zone coincides with second physiographic transition with high rainfall and thick vegetation and the headwaters are semi-arid with thin vegetation cover. The size of the bedload in this zone ranges from more than a meter to couple of tens centimetres. The upper reaches, at places forms deep and narrow gorges showing rapid vertical erosion. The zone II is characterized by gentler hill slopes and thick vegetation cover. The cannel has lower channel gradient (~8 degrees) and suspended load dominantly constituting the sediment load. A location plot of the all damage elements on geological when analysed in conjunction to geomorphic profile suggests that landslides and other disaster elements cluster in the two zones that are mainly controlled by orography and deep earth structures and thus carry a sense of predictability. The paper will discuss the details accordingly.

SAR Remote Sensing Based monitoring of Landslides in Mangan Town, Sikkim

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In this study, we have retrieved Remote sensing-based Land deformation velocity. The study area is Mangan Town in North Sikkim district of Sikkim state of India. Raffong Khola (river) bounds Mangan Town area in North & Ramet Kyong Khola is present in the south of Mangan. This area is delineated as a high & very high hazard zone. The Persistent Scatterer Interferometry Technique was implemented, which utilizes Time-series Satellite Radar Images. Fifty-one images of Sentinel-1 C-band SAR data from March 2018 to November 2019 was used for retrieving velocity. Atmospheric Phase Screen was implemented for the removal of phase induced due to atmosphere. 20 mm/year Line of sight velocity was retrieved. The area is unstable, as verified by the detailed field study conducted by the Sikkim State Disaster Management Authority.

Assessment and Characterization of landslide damming along the Tista river valley in the Sikkim Himalaya, India

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Damming of a river by the landslide is a natural geomorphic process in the Himalayan terrain, and is common in the mountainous terrain. This damming may be short lived or may occur for a longer period ranging in time from few days to tens and hundreds of years. It may either be partial, or complete. Stability assessment and characterization of the landslide dams may be assessed using numerous geomorphic indices. Some of these are Blockage Index (BI), Dimensionless Blockage Index (DBI), Annual Constriction Ratio(ACR), Morphological Obstruction Index (MOI), Hydro morphological Dam Stability Index (HDSI). These indices are extensively being used and mainly utilizes combination of two or more morphological attributes like landslide length, width, depth, volume, channel width, local channel slope and upstream catchment area. Each of these indices characterizes and evaluate a particular condition of potential dam formation in the river valley along with its stability condition.

In the present study, seventeen landslide have been identified using Tri-stereo Pleiades satellite imageries along the Teesta river valley between (i) Rangpo-Chungthag-Lachen and (ii) Rangpo-Chungthang-Lachung corridors where there is a possibility of damming the river by sliding materials directly into the Teesta river. For each landslide, all the geomorphic indices have been calculated. It has been observed that of the all the calculated BI, ACR, MOI indices, BI is more conservative in assessing the formation of landslide dam. It represenets the 14 sites with possibility of "No Dam Formation" and 2 sites with "Uncertainity" about Dam Formation, whereas ACR represents 3 sites with the possibility of "Dam Formation" and 5 with "Uncertainity" about dam formation and 8 sites with the probability of "No Dam Formation". Further, between HDSI and DBI, DBI is more conservative in assessing the instability of the landslide Dam. Representing 12 Stable Dam sites and 3 Unstable Dam sites, whereas HDSI represents unstability at all the locations. It has been concluded from the calculation of different geomorphic indices, it is difficult to assess with certainity the chances of formation of landslide dam and its stability.

Landslide Early Warning in Indian Context

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India, the seventh-largest country in the world apropos of area, is persistently being knocked by landslides of varied magnitude throughout the history. Despite of our increasing knowledge on the subject, the damage tolls due to landslides are on rise during monsoon in hilly terrain. Hence, landslide prediction on temporal scale is a viable option for risk reduction. Landslide early warning (i.e., temporal prediction of landslides) on local or catchment scale can be achieved in two different ways such as unmanned aerial vehicle (UAV) based landslide early warning (LEW) and geo-integrated rainfall threshold model based LEW. An attempt has been made towards deriving local rainfall thresholds for landslides based on daily rainfall data in and around Chamoli-Joshimath region of the Garhwal Himalayas, India. However, such threshold models do not consider the landslide mechanism involving key factors like surface and sub-surface geometry and material characteristics. Efforts are being made to improve upon existing rainfall threshold based LEW system. Further, low cost ground instrumentation based real-time monitoring for LEW can also be an alternate effective risk mitigation measure for site-specific perennial severe landslides and will be useful for community and traffic control on roads and railway tracks in hilly terrain. In this direction, a Landslide Observatory with wireless conventional instrumentation for real time monitoring of ground deformation and hydrologic parameters has been established at Pakhi Landslide in Garhwal Himalayas, India. The measurement sensors include in-place inclinometers (IPI), piezometers, wire-line extensometers and an automatic weather station (AWS). Efforts are now being made to develop low cost indigenous monitoring sensors, IoT nodes for sensor networking and cloud based real time monitoring software for site-specific LEW under National Mission on Himalayan Studies (NMHS). The present paper will discuss the key issues in the process of developing LEW system in Indian context.

Geology and geomorphological control of landslides in the Sikkim Himalaya, India

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Sikkim Himalaya is known for the occurrence of numerous natural hazards, particularly landslides and earthquakes. Landslides may occur by itself or may be succeeded during the earthquake. It is controlled by numerous geological and geomorphological factors besides the anthropogenic pressures on the landmass. The spatial distribution of xx active landslides in the North and the East Sikkim, mainly along the 95 km long Lachen - Chungthang - Mangan - Rangpo transect along the Teesta river were studied with respect to the geological and various geomorphic indices, like steepness index, valley floor width to valley height ratio, swath profile, and longitudinal profile of the river. All these indices indicate the tectonic active nature of the area. Based on various geomorphic indices, the studied transect has been divided into following three zones:

i) Zone I:- between Lachen and Chunthang: This zone is ~22 km in length and lies in the higher Himalaya. It is characterised by steep river gradient of the order of ~50 m/km, steep valley sides slopes, and very less precipitation. In this zone, three major knick points along the river have been observed which are indicated by high steepness index. These knick points are dominantly marked by 14 rock avalanches and 12 debris slides in the area.

ii) Zone II: Between Chungthang and Rangrang: This zone is ~23 km in length and also in the Higher Himalaya, to the north of the Main Central Thrust (MCT) which passes in the vicinity of Rangrang. It is also characterised by steep river gradient of the order of ~ 37 m/km. Further north of Chungthang there is steep rise in elevation, which act as a rainfall topographic barrier, therefore this zone is characterised by higher precipitation. Two prominent knick points along the river have been observed in this zone. This zone is dominantly characterised by 17 rock avalanches and 10 debris slides.

iii) Zone III: Between Rangrang and Rangpo: This zone is ~50 km in length and lies in the Lesser Himalaya. The river gradient in this zone is ~12 m/km. This zone is characterised by high valley floor width to valley height ratio, and is dominated by 16 debris slides.

Mapping vulnerable zones of Srinagar region, Garhwal Himalaya

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*N*H- 58 is the major pilgrimage transportation route to Kedarnath and Badrinath in the Garhwal Himalayas. Number of landslides are witnessed every year on this road corridor causing a lot of distress to locals and commuters. Stability assessment of road cut slopes along such highways is therefore very important. In the present study slopes of Srinagar area have been selected for the detailed geological and geotechnical investigation and evaluation of slope stability. These sites are selected on the basis of differing lithology, varying slope morphology and difference in mode of failure and are analysed for their potential degree of stability using slope stability assessment techniques. Three critical landslide zones have been identified in this area. Further an attempt has been made to do catchment based microzonation of Kaliasaur landslide zone using LHEF ratings, with a view to demarcate the most vulnerable slope areas which are susceptible to failure. Catchment facets which belongs to present failure process and which are near to failure are clearly been demarcated in this study. The results are been compared with evaluated values of SMR and CSMR and are found to be in good agreement with each other. Catchment based landslide susceptibility mapping can be applied on a large area and can further help in identifying vulnerable slopes. This can be very useful for adopting suitable measures for stabilizing the hill slopes.

Spatial Prediction of Landslides using Machine Learning techniques in the Bhagirathi Valley, Uttarakhand Himalaya, India

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Landslide is one of the most common hazard in the Himalayan terrain. It is caused by number of factors, including both internal and external factors. Therefore its prediction in space and time is very challenging. There are many qualitative and quantitative techniques to predict the spatial occurrence of the landslides. With the advancement of technology machine learning techniques are widely used now-a-days for the spatial prediction of the landslides. In the present study landslide susceptibility mapping using Support Vector Machine (SVM) and Random Forest (RF) methods was carried out in the Geographical Information System (GIS) platform for the Bhagirathi river valley, located in Garhwal Himalaya. For this, a detailed landslide inventory, using high resolution satellite data and extensive field survey was prepared. Landslide conditioning variables such as slope, aspect, profile curvature, plan curvature, geomorphology, lithology, landuse landcover, lineament, road, drainage, lineament and normalized vegetation index (NDVI) were taken into consideration. The weighted landslide conditioning variables were produced using Information Value (IV) method. It has been observed that slopes having slope angle ranging between 50° and 60°, south and southwest directed slopes, and slopes made up of augen gneisses, migmatic gneiss and biotite gneiss have shown high positive correlation with the occurrence of landslides. Though augen gneiss, migmatic gneiss and biotite gneiss are in general harder rocks but these lithologies in the study area belongs to MCT zone. The results obtained indicates that ~ 33.52% of the study area lies in high susceptible zone, 45.5% of the study area lies in medium susceptible zone and ~20.97% of the total study area lies in low susceptible zone. These results were validated using validation dataset of landslide with the Area Under Curve (AUC) method. The AUC values of SVM is 0.87 and RF is 0.901, thereby indicating high prediction rate for spatial modelling of landslides.

Landslide studies in Uttarakhand by Geological Survey of India: an overview

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The Uttarakhand state, being nearly wholly located in the Himalaya, known for its very complex geomorphic, geological and meteoric conditions. As a result the state is sensitive to natural disasters of many kind of which landslide is most widespread and menacing such that every year during monsoon the state suffers extensive damages to life and property. As per the surveys conducted by the GSI, about three-fourth of the total area of the state is prone to landslide. And this compares very high against the figure of ~12% of the country is landslide

prone. A comprehensive and systematic approach to reduce the menace caused by landslides is needed for a sustainable development plan of this hill state. GSI had been involved for landslide studies in the state since the time of Sir R. D. Oldham who studied the slope stability problem of the Nainital area way back in 1880. Since then, GSI had been involved in this state for mitigation of landslide hazards in various ways.

Many townships, road corridors, pilgrimage yatra routes, river catchment/basins etc. are mapped systematically and specifically for landslide susceptibility on different scales like i) macro-scale (1:50,000/25,000) and meso-scale (1:10,000). Routinely, GSI is involved in many site-specific (<1:5,000) landslide investigations and post-disaster rapid geotechnical assessment of landslides. Some such notable site-specific work done in recent times by the GSI include Varunavat Parvat landslide [Uttarkashi], Lambagar landslide [Chamoli], Semi village subsidence zone [Rudraprayag] and Bhatwadi landslide [Uttarkashi] etc.

Under a flagship program of GSI, the National Landslide Susceptibility Mapping (NLSM), all areas falling in the hilly tracts of Uttarakhand, would be completed for landslide susceptibility mapping on 1:50,000 scale by March 2020. Areas are identified & prioritized for mesoscale studies (1:10K) based on the input from the Macroscale landslide susceptibility map, field inputs and discussion with the stakeholders. For developing a standardized method for doing meso- scale landslide susceptibility mapping, GSI is presently engaged on a couple of pilot projects on some critical sites in the state. In near-future, such work would lead to formulation of Standard Operating Procedure (SOP) for mesoscale landslide susceptibility mapping in the NW Himalaya.

GSI is also involved in the state on research projects for development of early warning system in collaboration with other agencies. On the other hand, GSI has developed a community based landslide warning systems based on rain-fall data and other landslide susceptibility parameters. Such systems have been tested by GSI in Darjeeling Himalaya and in Nilgiri Hills. Presently, GSI is planning to use the same methodology in Rudraprayag district in Uttarakhand. Once developed, this would be community based landslide early warning system in Uttarakhand.

Thus, a systematic multi-pronged approach presently being undertaken by the GSI would help Uttarakhand state to effectively tackle and mitigate landslide hazards to a large extent.

Landslide Movements Related to Rainfall. Analysis of a Statistical model from Sonamarg to Kargil, along NH 1D (J&K)

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Landslides are among the great destructive factors which cause lots of fatalities and financial losses all over the world every year. The aim of this research is to produce a landslide susceptibility assessment using weights of rainfall events and landslide occurrence models based on (land-area-based/location) using remote sensing and geographic information system (GIS) for the National Highway 1D from Sonamarg to Kargil, Jammu and Kashmir. 317 landslide locations were mapped along the National Highway ID using past reports from the Srinagar, Haripora, and Kargil Border Roads Organisation, aerial photographs, inclusive field surveys and higher resolution Google maps. GCPs were used to accurately define the location of landslides. The analysis of the data from 1992 to 2016 revealed that the study area has received highly erratic and uneven distribution of precipitation. The present study reveals that 213 landslide events were found to have a significant correlation with rainfall occurrence and remaining landslide episodes seem to have occurred due to lithology, slope, and other factors. The landslides were categorized into five categories on the basis of the frequency of occurrence over a period of time from 1992 to 2016. The results of the statistical analysis with the general linear regression model showed that the highest landslide occurrence is explained by rainfall increase with some exceptions where landslide occurrence seems to be related to other factors as well. There is a regular incidence of traffic disruptions along the Zojila Pass. Thus there is a vital need to mitigate the landslide hazard particularly to avert the disruption from Sonamarg to Kargil which causes enormous inconvenience, economic and human losses.

Geomorphic Evaluation of Bhyunder Ganga Catchment, Chamoli District, Uttarakhand, Using: GIS Approaches

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Geomorphology is the science of evolution of landforms in terms of its lithology, structures, basin geometry and other morphometric factors. In this study, various gemorphological parameters covering the Bhyunder Ganga catchment are studied. The main objective of this study was to map and classify the land system into further various landform units and features through geomorphic approaches. Geomorphologic maps were prepared using Satellite images (Landsat ETM+, TM, MSS, ASTER, SRTM) and digital SOI (Survey of India) topographic sheet of the region. The map was further updated with the field data. Digital Elevation Model (DEM) was generated based on the topographical sheet and ASTER data and was used for the preparation of the relief map, slope map, aspect map and 3D visualization map. In addition, drainage map with the help of topographical sheets, and various thematic layers have also been developed. Land use/cover of the study area has been analyzed for the time periods of 2018-19. It has been noted that the major proportion in land use is the snow cover (~53.20%). Other landuse are barren land (22%), dense forest, open forest and the built up area. The water bodies occupy only 24.8% area of the catchment. Various theme maps including erosion intensity, LST were generated in the GIS environment and were analysed to assess the morphology and the instability in the catchment area.

Morpho-structural approach to assess slope failures in the Kali River Valley, Kumaun (Uttarakhand) Himalaya, India

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The objective of this study is to evaluate the role of tectonics in spatial distribution of landslides between Jauljibi and Dobat villages in the northern segment of Kali valley, Kumaun Himalaya. Towards this, various studies such as steepness index (K_{sn}), valley floor width to valley height ratio (V_f), terrace slope analyses, topographic swath profile, longitudinal river profile and the topographic bedding plane intersection angle (TOBIA) were studied. The study area lies in the metasedimentaries of the Inner Lesser Himalaya and is characterized by various thrusts and faults including South Chipplakote Thrust (SCT), Lasku Fault (LF), Dharchula Fault (DF), Ghatibagabar-Kalika Fault (GKF), Rauntis Fault (RF) and Berinag Thrust (BT). A detailed inventory of active landslides, depicting 94 landslides was prepared. All these landslides are debris slide. It has been noted that 28% landslides are 'Small' sized (area affected < 1,000 m^2), 35% are 'Moderate' (area affected ranges between 1,000 and 5,000 m^2), 12% are 'Large' (area affected ranges between 10,000 and 5.000 m^2) and 25% are 'Very Large' sized (area affected > 10,000 m^2).

The Ksn index in the area ranges from 0.6 to 714. The higher Ksn values are recorded across the LF (near Dharchula), GKF (near Kalika and Dhap) and RF near (Jauljibi). In general, the locations with higher Ksn values correspond with the prominent knickpoints in river longitudinal profile. Topographic swath profile also indicate abrupt increase in elevation at these locations. Since Ksn and V_f have inverse relations, the locations with higher Ksn are marked with low V_f values. In the entire study area, six levels of terraces have been observed, and across GKF, 20 m offset in the level has been observed. All these indicate that the area is tectonically very active and has also been further corroborated with the presence of higher concentration of large to very large sized landslides.

The topographic slopes of the area has also been classified into cataclinal, orthoclinaland anaclinal using TOBIA index. This indicate that ~74% of the slopes are orthoclinal, 25% are cataclinal and only 1 % is anaclinal. This shows that unstability in the area is also structurally controlled.

Landslide Vulnerability Atlas along Rishikesh-Kedarnath Highway, Uttarakhand: An overview

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Landslides are one of the most critical agents in shaping the earth's surface and at the same time one of the most devastating natural hazards. These are more frequent in the mountainous region of the world and Himalaya is no exception. The tragedy of Kedarnath, Uttarakhand in 2013 had created havoc not only in India but across the world where numerous landslides of different types brought substantial loss to life, infrastructure, and properties. In the wake of the disaster, the Department of Science and Technology, India initiated research on large scale geological and geotechnical mapping along Rishikesh – Kedarnath route in Uttarakhand. The route from Rishikesh to Kedarnath has many landslides prone zones due to its complex geology, topography and steep slopes, which includes natural as well as human-made slopes. Various institutes and universities had carried out the study intending to prepare a vulnerability atlas of Rishikesh-Kedarnath Highway, Uttarakhand. Geological mapping in the 1:10,000 scale was carried out continuously along the road section, which shows various lithology, structural discontinuities, and damage zone linked with slope instability related issues. Geotechnical assessment of slopes was carried out applying rock mass and slope mass characterization. Slope stability analysis was also carried out by limit equilibrium and finite element modeling. The outcomes of geological and geotechnical mapping were depicted in a manner such that the atlas will be helpful for planners, scientists, and various stakeholders, along with ordinary people, to utilize the outcome for sustainable development.

Landslides Susceptibility Using Fuzzy Logic Approach in the Eastern Sikkim Himalaya, India

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Landslide is one of the most common natural disaster in the Sikkim Himalaya causing great loss to humans and society. East Sikkim district of the Sikkim is of strategic importance as it houses Gangtok, the capital township of the state, and the important Gangtok - Changu Lake - Nathula pass corridor, en route to Kailash Mansarovar. Therefore it is essential to understand the temporal probability of landslides occurrence in the region. In the present study, landslide susceptibility of the East Sikkim district of the Sikkim was undertaken using fuzzy logic utilising frequency ratio approach. The spatial distribution of all the 110 active landslides were prepared using high resolution Pleiades satellite data and extensive fieldwork. Of these landslides, 70% randomly distributed landslides were used for the preparation of the landslide susceptibility map and the remaining 30% for the validation of the map. The thematic layers of all the possible eleven causative factors of landslides such as

lithology, slope angle, slope aspect, elevation, curvature-plan, curvature-profile, distance to drainage, road & thrusts and vegetation cover were prepared and the frequency ratio coefficient for each factor was computed.

The susceptibility maps thus prepared has been classified into five classes ranging from very high, high, moderate, low and very low susceptibility zones, each covering an area of ~10%, 20%, 30%, 15% and 25%, respectively. These results were quantitatively validated using area under curve for the success rate curve and the prediction rate curve, which is 90.12% and 83.87%, respectively.

Numerical analysis of a landslide affected slope in Indian Himalaya with cohesionless soil matrix

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Stability analysis of a slope in the Kumaon region of Uttarakhand state of India was performed because this slope had faced a landslide due to deforestation and minor seismic activities in that area as per the records of Geological Survey of India. As per the earthquake zonation map of India, the slope lies in Zone IV, corresponding to high seismicity. The study slope is 8 m high and is nearly vertical with average angle (with vertical) as 10º. The numerical analysis was performed under pseudo static conditions which was later validated using the software PHASE^2, Rocscience, 2011. Mohr-Coulomb shear strength criteria is adopted for soil material and grouted nails are modelled as bolts with parameters like modulus of elasticity, diameter of nails and peak pull out resistance of the nails. The slope was found to be unstable under pseudo static conditions with computed factor of safety of 0.41. But by using grouted nails, the factor of safety is increased to 1.48 in seismic conditions.

Seismicity and b -value analysis for the hazard estimation around the Kumaun - Garhwal Himalaya using the Seisan software

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Kumaun – Garhwal region continues to accumulate the built-up of strain energy like many other regions of the Himalaya due to under - thrusting of the Indian plate beneath the Eurasian plate. This segment of the northwest Himalaya is seismically the most vulnerable section of the region and thus has potential to suffer great earthquakes, mainly because there has not been release of energy as great earthquakes between the seismic gap of this region,

suggesting that this region has high stress accumulation. There are some historical earthquakes around this region like 1505 Kumaun - Garhwal region (8.2 M), 1991 Uttarkashi earthquake (6.6 M), 1999 Chamoli earthquake (6.3 M). In addition to these, two latest earthquakes are also recorded, these are December 14, 2005 in Chamoli earthquake (5.3 M) and July 23, 2007 earthquake (5.0 M). Both these earthquakes were felt in Delhi. Recently, in June and July 2010, a series of low to moderate earthquakes have also been recorded near Ranch and Dhura in Dharchula, Uttarakhand. Besides, we have also located 120 earthquakes of the local magnitudes between 2.5 and 5.6 from one-year data collected from the installed seismic stations of Bhatwari (BHWT), Haridwar (HARI), Tissa (TISA), Pithoragarh (PITH), Munsiyari (MSRI), Rewalsar (RWSR), Garurganga (GRGA) and Tehri (THRI) located around the Kumaun - Gharwal region. The seismicity pattern and calculation of b-value analysis around the study region with one-year data enhance the knowledge regarding the hazard estimation. The variation in b- value indicates the presence of stress accumulation and can be used as one of the component of precursory signature for future earthquake. Moderate b-value around the Himalayan region might release the energy in the form of great earthquake due to high stress accumulation in the region and this may produce numerous landslides in the area as in the case of 2015Gorkha earthquake.

Extreme hydrological events in the Mandakini river valley: Present and past

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In the recent years, the Himalayan eco-system is increasingly being threatened due to anthropogenic intervention for various developmental purposes. As a consequence, it is feared that the sustainability and its stability is threatened. The geomorphic expression of the human intervention in the region is being increasingly felt which is manifested by frequently increasing incidences of landslides in areas that were otherwise considered stable. To quote few examples are the 1998 Madhyamaheshwar valley landslide and 2003 Varunavat landslides, and the recent example is the June 2013 flood in the Mandakini river valley which has few parallels in the recent history. This flood has become a subject of scientific debate whether it was a natural climatic phenomenon or was amplified due to increasing human intervention in the river valleys.

In this presentation, we will be presenting the detailed investigation of the June 2013 flood along with presenting our new finding on the geomorphic and sedimentological evidences of past floods in the valley. Field observations supported by the existing chronology from the Mandakini valley indicate that during the mid-Holocene, there were multiple incidences of events similar to June 2013 implying the sensitivity of the valley towards high magnitude floods. The emphasis would be on the factors responsible for generating high magnitude floods in the mid-Holocene and its implication on the evolution of the valley morphology.

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