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Editor-in-Chief

Landslides are one of the common catastrophic phenomenons in the hilly as well as coastal states of the country. Every year the disaster engulfs huge monetary assets and harmony of the ecosystem beside precious lives. In India, the monsoon season has become synonymous to the landslides. The arrival of monsoon precipitation is accompanied by the apprehension of occurrence of some deadly landslide episodes around the territory of India. Further, the extreme weather events as resultant of climate change have augmented the frequency and intensity of this disaster across the globe. The irony is that to fulfil the insatiable carving of development and growth, we have ignored the sustainability of the slopes on which our infrastructures and structures are built. Today, anthropogenic activities are one of the major causes of slope failures.

As per the mandate of Disaster Management Act 2005, National Institute of Disaster Management has always stridden forward to create disaster resilient India through its training, research, documentation and publications. The Institute publishes a bi-annual Journal titled "Disaster & Development" with an aim to provide a common platform to the researchers, academicians and others for publication of their unique and innovative research work on all aspects of the disaster management. The first issue of the journal was released in the year 2006.

The current special issue of the journal covers research works on all facets of the landslides. The papers were reviewed by renowned persons having years of experience and expertise in the field of landslides management. I am hopeful that this issue on landslide will be valuable for the readers in understanding the landslide hazards, associated risks and also the prevention and mitigation of landslides.

Major General Manoj Kumar Bindal, VSM

Editorial

Landslides have always been a nightmare to the communities living on the fragile slope across the nation. From the Malpa landslide, Uttarakhand (1998) to the Kavalappara Landslide, Kerela (2019) the country has witnessed a number of horrendous episodes of this disaster. Landslides not only slaughter the precious lives but also eradicate the psychological well beings of the affected communities. It not only destroyed the valuable infrastructures and structures but also the picturesque ecosystem. There are a number of adverse impacts of the landslides on communities as well as the environment and sometimes these are irreparable. Further, landslides can accompanied other disasters as a secondary one to exacerbate the suffering of the affected people. The disasters that can initiate landslides include earthquakes, floods, flash floods, cloud burst, glacial lake outburst floods and landslide dammed lake outburst floods. In Sikkim, more than hundreds of landslides were occurred as a consequence of the earthquake in 2011. Among those landslides, some were reactivated and others were induced for the first time. Nepal earthquake (2015) is another instance when numerous landslides were induced due to seismic activities. The Kedarnath tragedy (2013) in Uttarakhand was resultant of glacial lake outburst floods which generated a number of landslides downstream side. There are many more examples that justified the multi-hazard profile of the landslides after other disasters. Apart from secondary disaster, landslides have capabilities to induce other disasters that include flash floods and tsunami. The Alaknanda tragedy (1970) is an example of the disaster created by the outburst of landslide dammed lake. Indonesia Tsunami (2018) illustrates the role of landslides in producing a tsunami.

Though the climate change is not a new phenomenon yet is the most talked issue in the current era. The main concern is the magnitude in which the changes are taking place and the risks imposed by them on communities and the environment. The need of the hour is to incorporate the quotient of climate change in our strategies for managing the landslides. Urbanisation and associated anthropogenic activities have also exposed more human population and slopes to the spectrum of landslides.

The consequences of landslides are avoidable or at least we can reduce them. For this, we need to adopt modern science and technology along with indigenous knowledge, appropriate monitoring and early warning system and most importantly enhancing the capacity of local communities in understanding the risk of landslides and the measures to combat them.

I am thankful as well as congratulate all the authors who have submitted their authentic research work in our journal. Hopefully, together we will be able to tame the risks of landslides on our societies and environment.

Surya Parkash, Ph.D.

Probabilistic Analysis of Slope Stability and Landslide Risk Assessment

Fomenko I.K.,* Zerkal O.V., Kurguzov K.V.* and Shubina D.D.***

Abstract

Provision of social and economic safety is one of the main concerns during territory development with high risks of landslides activities. This issue requires geological risks assessments. Probability evaluation of landslides activity is one of the main parameters in the quantitative evaluation of geological risk.

An application of probability analysis for quantitative evaluation of slopes stability is proposed for risk assessment. It allows characterizing threats by the means of quantitative evaluation. The substantial idea of probability analysis is probability function determination of the factor of safety (FOS) that depends on the input distribution of the physical and mechanical soil parameters of the analyzed slope, as well as other slope activity factors.

This article shows the results of slope stability probabilistic analysis and of the quantitative risk assessment of landslide activity at the studied construction site. For the implemented risk analysis an assumption was made that economic losses depend primarily on the deformation level of the structure foundations.

Keywords: slope stability, probabilistic analysis, landslide risk assessment

Introduction

Currently, considering increasing economic development of territories affected by dangerous geological processes, including landslides, special attention during site investigations is paid to the safety of the structure that is planned to be constructed. The modern concept of complex systems operating assumes a transition from the ideology of "absolute security" to the concept of "acceptable risk." This requires risk

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analysis and development of the risk management system, which means reduce risks to an acceptable level. Thus, the geological risks assessment is currently one of the most important areas of work to ensure the safety of territories, constructed and designed buildings and people living in them. It should be noted that the probability of landslide activity is currently considered as one of the key characteristics in the geological risk quantitative assessment (Bell and Glade, 2004; Crozier and Glade, 2004; Dai et al., 2002; Fell et al., 2007; Glade and Crozier, 2004; Kappesetal., 2012; Pendin and Fomenko, 2015; van Westen et al., 2006; Zerkal, 2009; Zerkal et al., 2014; Fomenko et al., 2018).

Probabilistic analysis in calculating the slope stability is becoming relevant in the world practice and is often used due to increasing understanding of the random variability of the characteristics of the physical and mechanical soils obtained during engineering survey. Considering the wide range of soil properties fluctuations, the probabilistic approach associated, besides all, with their variability assessment, caused, in particular, by climate change, allows us to look at the analysis of landslide hazard more universally from a new perspective.

It should be noted that the conservative deterministic methods of the slope stability calculation widely used at present take into account the variability of landslide formation factors indirectly: their statistically determined design values are used in the numerical models. Safety factors obtained on the basis of such calculations do not really determine the actual level of harm, since it is impossible to establish a relationship between them and the probability of slope failure.

Existing Restrictions of The Use of Slope Stability Quantitative Estimates in Risk Analysis and How to Overcome Them

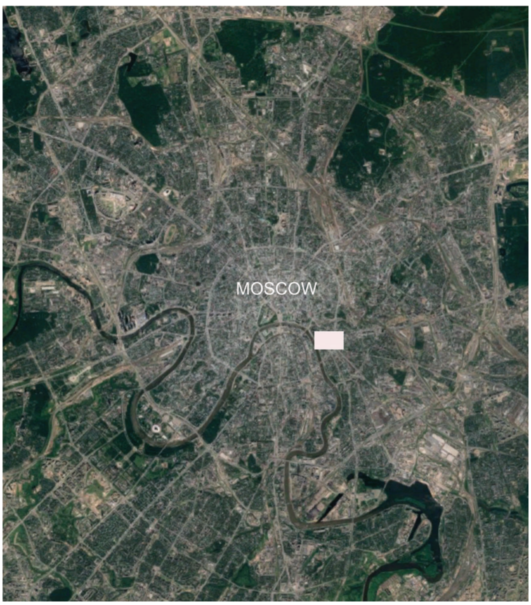
Currently, it is generally accepted to provide a factor of safety (FS) as the resultant value of the quantitative assessment of slope stability. FS is considered as an indicator of the possibility of slope deformations associated with a landslide (Bishop, 1960; Fomenko and Zerkal, 2017; Fomenko et al., 2016; Janbu, 1954; Kang et al., 2019; Krahn, 2004; Morgenstern and Price, 1965; Zerkal and Fomenko, 2013). At the same time, the obtained FSvalue used within the frames of the conventional approaches characterizes the state of the slope instantaneously (Fomenko and Zerkal, 2017; Fomenko et.al., 2016; Kang et al., 2019; Zerkal and Fomenko, 2013). In other words, the calculated value of factor of safety characterizes the state of the slope exclusively at the time when the slope parameters used for calculations were obtained (as a rule, these are mean values of the physical and mechanical properties, averaged statistically). At the same time both in natural and technologically altered conditions the state of soils (as well as their characteristics) in the slope massif are significantly variable under the influence of different factors. However, the traditional "generally accepted" approaches to the slope stability quantitative assessment are based on the idea of "static", time-invariant properties of soils composing the slope massif. Undoubtedly, this is a significant limiting factor in predicting (in time) the possible development of landslide processes, not allowing us to assess the probability of a negative scenario implementation (or hazard) for changing the engineering and geological conditions when the slope becomes unstable.

One of the ways to overcome the existing limitations of quantitative slope stability assessment methods when performing risk analysis is to use probabilistic analysis, which allows characterizing the landslide activation hazard (in terms of probability). The essence of probabilistic analysis in the slope stability quantitative assessment is to obtain the probability distribution function of the safety factor depending on the probability distribution functions of the physical and mechanical characteristics of the soils composing the slope, as well as other factors affecting the development of landslide processes.

Probabilistic Analysis of Slope Stability

The probabilistic analysis in the slope stability quantitative assessment was performed at a10-12 m high right-bank slope of the Yauza River valley in the central part of Moscow (Fig. 1). In close proximity to the slope, the construction of a high rise building is planned.

Fig. 1: The site location in Moscow, Russia



The upper part of the geological section within the studying area is composed (from top to bottom) by man-made soils (units 1.2, 1.3), Quaternary moraine loams of various consistencies (units 5 and 6), Quaternary fluvio-glacial, glacial-lake and lake sands (units 7, 7a, 8, 8b, 9 and 10), which are underlain by upper and Middle Jurassic clays and loams (unit 11), and the Upper Carbonic limestones. In the channel part of the river valley alluvial formations (items 2, 2a, 3 and 4) are developed. The geomechanical design scheme of the slope is shown in Fig. 2. The cohesion and internal friction angle were considered as independent values.

Fig. 2: Geomechanical design scheme of the right-side slope of the Yauza River (Moscow, Russia)

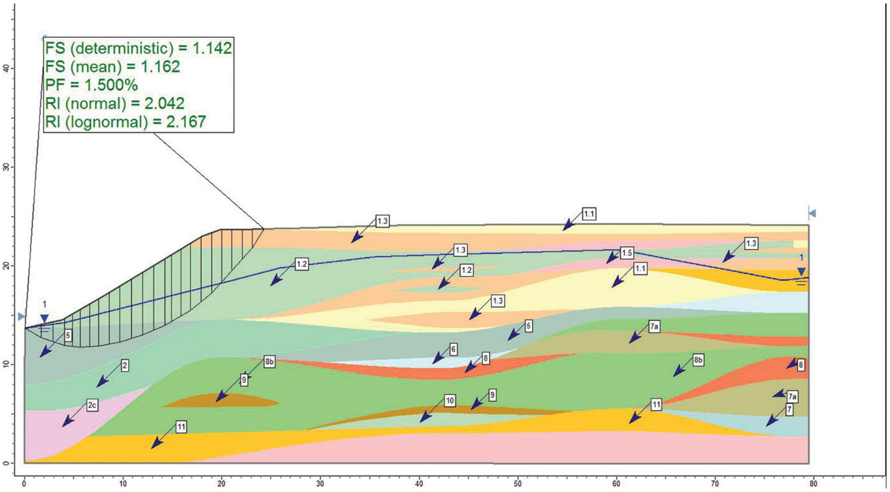


Table 1: Soil properties values and their statistic processing results used for factor of safety calculations

Soil unit	Properties	Average value	Standard deviation	Deviation to minimum	Deviation to maximum
1.2	Cohesion	14	4	4	4
1.2	Internal friction angle	17	5	5	5
1.3	Cohesion	20	5.6	9	8
1.3	Internal friction angle	31	4	5	4
2	Cohesion	2	0.5	2	1
2	Internal friction angle	34	2	4	6
5	Cohesion	12	4	5	6
5	Internal friction angle	19	1.5	1	3

Slope stability was assessed using three calculation methods: Janbu (Janbu, 1954), Bishop (Bishop, 1960), and Morgenstern-Price (Morgenstern and Price, 1965), of which the Morgenstern-Price method is the most rigorous. All of these methods in traditional applications are deterministic since it is assumed that the soils strength characteristics are known and can be set in the form of averaged values used for calculations. However, as noted above, obtaining “accurate”, “complete” data that would characterize the slope massif entirely is practically impossible.

A peculiarity of the performed slope stability quantitative assessment is to use for calculations not the averaged values of soil properties, but the entire data set of the soils strength parameters. It should include the properties distribution function, minimum and maximum values, as well as the standard deviation. This approach to taking into account the characteristics of soils provides more complete use of information about their variability obtained during field and laboratory studies. It allows assessing their influence on the slope massif stability. As a result of using the proposed approach a probabilistic quantitative estimate of the slope stability was obtained, which additionally, in contrast to deterministic estimates, characterizes the minimum, average, and maximum values of the slope stability, and the standard deviation in the factor of safety distribution in the test series used for calculations. A description of the methodology for performing a probabilistic quantitative assessment of slope stability can be found in (Zerkal and Fomenko, 2016). The proposed approach to taking into account the characteristics of soils, on the one hand, provided a more complete use of information about the variability of the properties of the physical and mechanical soils, and, on the other hand, made it possible to perform a probabilistic quantitative assessment of the slope stability.

A quantitative stability assessment of the considered right side slope of the Yauza River showed that for the given indicators of soil properties variability, the slope is stable (average FS = 1.03 ÷ 1.162, depending on the calculation method). At the same time from Figure 3 which shows the integral probability curves for the slope stability values variability, the slope failure probability for the given soil properties variability is from 1.5 per cent (Morgenstern-Price method) to 33.3 per cent (Janbu method). For further analysis, it is advisable to accept the results obtained by the most rigorous Morgenstern-Price method.

The summary results of slope stability probabilistic quantitative assessment are given in Table 2, the cumulative distribution of the safety factor obtained by various methods is shown in Fig. 3.

Fig. 3: Integral probability curves for the stability of the right-bank slope of the Yauza River (Moscow, Russia) at the study site

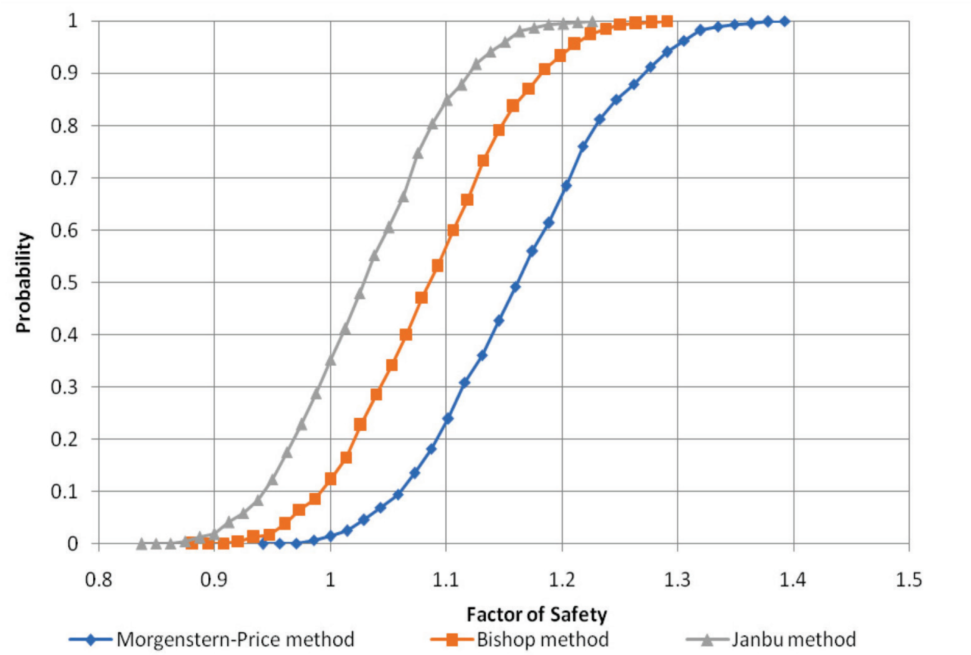


Table 2: Probabilistic quantitative slope stability assessment obtained by different methods (without taking into account the quality of initial engineering geological information)

Factor of safety	Morgenstern-Price method	Bishop method	Janbu method
Average value (deterministic approach)	1,16	1,09	1,03
Standard deviation	0,08	0,07	0,07
Minimum	0,95	0,89	0,85
Maximum	1,38	1,29	1,22
Probability of landslide process development (Safety factor <1)	1,5%	12,3%	33,3%

As can be seen from Table 2, a quantitative assessment of the slope stability performed by various methods resulted in close average values of the factor of safety, which differ depending on the used calculation method. Following the traditional approach to the slope stability analysis, they obtained FS values would become the basis for the conclusions that the slope is generally stable but is close to the limiting equilibrium state. It would be impossible to draw any additional conclusions base on the obtained FS values without additional calculations.

At the same time, the analysis of the slope deformations probability obtained by the selected calculation methods allows us to evaluate the influence of the calculation method on the resulting estimates of the landslide activation possibility (Table 2). The probability of landslide development in the considered area obtained by various methods differs more than 20 times. The highest probability (33.3 per cent with the minimal average FS value) was obtained by use of the Janbu method. The lowest values were obtained by use of the Morgenstern-Price method (1.5 per cent with the maximal FS average value).

Geological Risk Assessment

The performed slope stability probabilistic analysis at the study site made it possible to obtain a probability index of the slope destabilisation. Taking in mind that close to this site the tall building is designed, it allows performing a quantitative assessment of the economic risk from the possible landslide formation. Use of this methodology is considered by Moscow regulatory documents (Guidelines, 2002).

The differentiated economic risk of landslide losses was estimated as the full and specific (reduced to the unit area) values of this risk according to the following formulas:

$$R_e(H) = P(H)*P_s(H)*V_e(H)*D_e,$$

$$R_{se}(H) = R_e(H) \ / \ S_o$$

where $R_e(H)$ and $R_{se}(H)$ – are correspondingly full (per cent of the building cost/year) and specific (per cent of building cost/m^2 year) damage risk from the landslide hazard H; P(H) – landslide hazard (H) realization within the certain area, numerically equal evaluated slope stability loss probability; $P_s(H)$ – geometric probability of object exposure by the landslide hazard H in the area; S_o – object area (m^2); $V_e(H)$ – economic vulnerability of evaluated object to the landslide hazard H; De – the object cost before the landslide hazard (accepted as 100 per cent).

The vulnerability values defined for surface deformations at the base of the building foundation adopted in (Guidelines, 2002) were taken as indicators of the designed building economic vulnerability. Obviously, the development of such deformations is possible due to the landslide displacements. The results of a quantitative assessment of the differentiated economic risk from the landslide processes development with the probability of slope stability values obtained using the Morgenstern-Price method variability are shown in Table 3.

Table 3: The differentiated economic risk assessment from the landslide processes development (according to (Guidelines, 2002))

The lifetime of building, years		50	
Footingarea, m^2		7736,8	
Designed values of deformation zone		area, m^2	1235
		probability	0,015*)
Affected area to the full footing area ratio		0,168	
Economic vulnerability of the building		average	0,01
		average max	0,04
Economic risk	average	full, %/year	$2,52*10^{-3}$
		specific, %/m^2·year	$3,43*10^{-7}$
	maximum	full, %/year	$1,01*10^{-2}$
		specific, %/m^2·year	$1,37*10^{-6}$
Expected full economic damage for 50 years, % of full cost	average	0,126	
	maximum	0,504	

Note: * The probability of slope stability loss, calculated with Morgenstern-Price method

The performed landslide risk calculation for the building designed near the studied slope showed that over 50 years of operation of the building, the average economic damage from landslide activity can count 0.126 per cent of the designed building cost, with maximum values reaching 0.5 per cent of the cost. The obtained landslide risk values for the evaluated building are not significant and apparently, the slope will not require additional strengthening measures.

Conclusion

Assessment of the hazardous geological processes' probability (including landslides) is one of the key characteristics in the quantitative assessment of the geological risk. Utilisation of the probabilistic slope stability analysis based on the elaboration of the probability distribution functions of the factor of safety depending on the probability distribution functions of the various soil characteristics provides data requires for risk analysis. The standard (deterministic) slope stability assessment does not allow obtaining the probability of landslide occurrence.

The results of the landslide risk assessment using the proposed approach can become the basis of the geological risk management both at the construction sites and for the regional landslide risk assessments.

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

Shovan L. Chattoraj,* Suresh Kannaujiya,* P.K. Champatiray,*
Raghavendra S.* and Shefali Agrawal*

Abstract

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

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

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

Introduction

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

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

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

Material and Methods

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

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

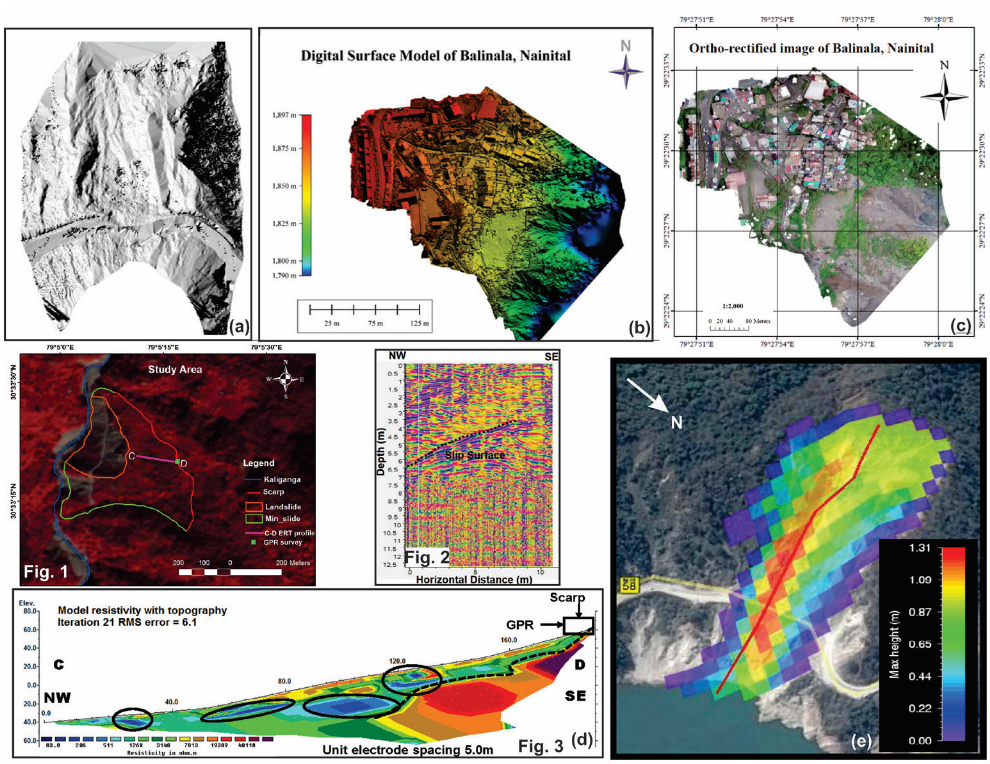
Geophysical technology was employed at Kaliganga river valley, close to Kalimath, situated in Rudraprayag district, covering an area of 5.64 to study a landslide scarp is approximately 685 m long located above the Kunjethi-Kotma road. The lithology of the area comprised mainly of metamorphic rocks and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

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

Results

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

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



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

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

Discussion

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

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

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

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

Conclusion

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

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Kinematic Analysis of Noklak Landslide, Tuensang District, Nagaland

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Abstract

A very complex landslide has plagued Noklak town in the eastern part of Nagaland for more than two decades. The magnitude of the landslide has grown both in its influence and coverage area of 1.84 sq. km in last few years affecting the only route connecting the International Trade Centre at Pangsha (Dan), uprooting many households, cultivated areas and also posing a threat to nearly one-fifth of the town population presently. It is incorporated in SOI toposheet no. 83 N/4 and lies in 95°00'39" E longitudes and 26°11'52" N latitudes. The present study aims to identify the causative factors of this land instability by employing the method of kinematic analysis of the slope material to determine the potential mode of failure. These analyses were performed from 1,195 joint attitudes collected from in-situ rock exposures in the field to determine the dominant joints that control the instability in the area. The strength of the rocks was calculated by Point Load Test data on 50 rock samples. Both Rock Mass Rating (RMR) and PLT value indicate poor rock quality and low values for the rocks. SMR (Slope Mass Rating) values for this slope fall in Class IV and results from the kinematic analysis shows both planar and wedge type of failure indicating several micro-slips within the study area and absence of firm bedding.

Keywords: Noklak; Nagaland, Kinematic Analysis; RMR; SMR; Landslides

Introduction

Nagaland, a north-eastern state in the Indian sub-continent is infested with landslides because of intense tectonic activities causing slope instabilities. Noklak town is situated in the eastern part of Nagaland that is characterized by rugged topography of moderately

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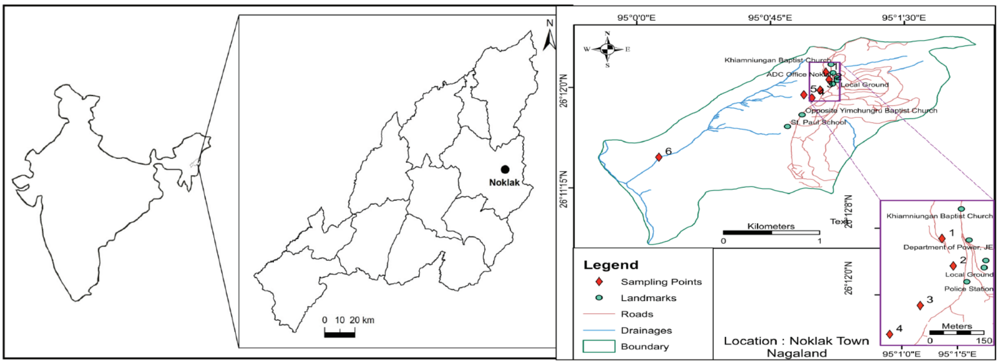
dissected structural hills and valleys with high drainage incisions and is located at 95°00’39” east longitudes and 26°11’52” north latitudes which are incorporated in Survey of India (SOI) topographic sheet no. 83 N/4. A minor land instability which initially started in 1980 at the south-western part of the town has aggravated into a major landslide affecting 1.84 sq. km. The area is occupied by weak lithology and with an average slope of about 50°, it is highly unstable and susceptible to slope failures (Fig. 1).

The present study investigates the landslide that was reactivated in 2004 and subsequent failure in the succeeding years. The main objectives of the present study are to ascertain the influence of geo-mechanical properties of rock on the slope instability, to determine the possible mode of failure and to develop appropriate mitigation measures.

Fig. 1: Map of the study area



MATERIALS AND METHODS

Rock Mass Rating (RMR)

The Rock Mass Rating, a geomechanical classification system for rocks developed by Z.T. Beinawski in 1972 and 1973considers various geological parameters that influence rock instability and represent them with one overall comprehensive index of rock mass quality.

The five parameters on the basis of which rocks are classified using the RMR system are:

- Uniaxial Compressive Strength of rocks (UCS): A strength characteristic of rock for evaluating rock mass classification and analyze slope instability (Thurro, 1997).
- Rock Quality Designation (RQD): Developed by Deere 1967, to provide a quantitative estimate of rock mass quality from drill core logs. RQD is defined as the percentage of intact core pieces longer than 100mm in the total length of the core.

- The spacing of discontinuities: The stability of rock slopes is significantly influenced by the structural discontinuity in the rock in which the slope is excavated. Persistence of discontinuities defines, together with spacing, the size of blocks that can slide from the face.
- Condition of discontinuities: Roughness of discontinuity surface such as joints, is the measure of the inherent unevenness and waviness of the surface of discontinuity relative to its mean plane.
- Groundwater conditions: This accounts for the influence of the water pressure, with particular reference to the underground excavation. It can be classified as dry, damp, wet and flowing (Bieniawski, 1989).

The strength parameters of the rocks are measured using the Point Load Testing machine (PLT) or Schmidt hammer. To analyse the rock samples collected from the field, the point load test is opted for. The point load strength index I_S is calculated using the following relation:

$$I_S = P / De^2$$

Where, P = pressure obtained at failure, De = equivalent diameter of the rock sample

In the case of point load strength index less than 1 MPa, Uniaxial Compressive Strength test (UCS) is applied. This low value may be the outcome of weak slope material influenced by the presence of water. Hence for shale, which is the dominant rock type in the affected area, the UCS equation (Singh et al, 2013) is given as

UCS = 14.4(PLI) (PLI = Point Load Index)

In the case of the use of Schmidt hammer for determining the compressive strength of intact rocks, the UCS equation employed (Deere and Miller, 1966) is given as

$$\text{UCS} = 6.9 \times 10^{(0.16 + 0.0087 R_n \rho)}$$

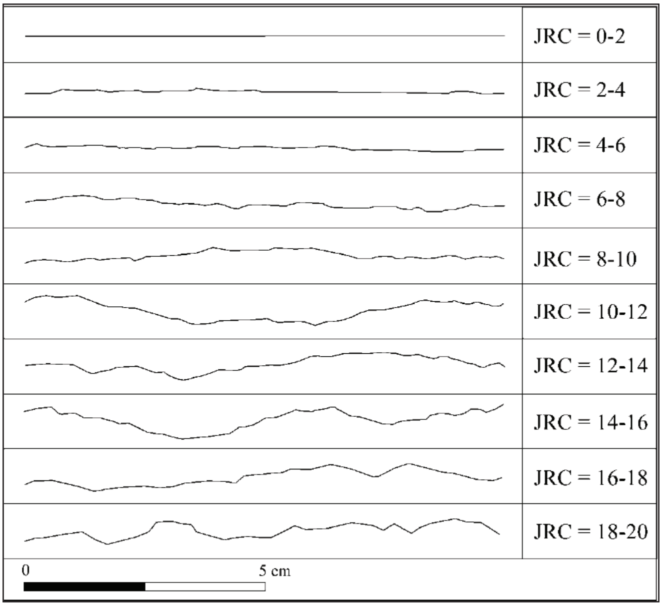
Where, R_n = Schmidt hammer rebound number, ρ = Rock density

Palmstrom (1982) estimated RQD from the number of joints per volume given by the following equation:

$$\text{RQD} = 115 - 3.3 J_v,$$

Where J_v = the sum of the number of joints per unit length for all joint sets, known as the volumetric joint count. The condition of the joint is inferred from the inherent surface smoothness or unevenness and waviness relative to the plane of the joint. Joint roughness can be felt by touch and is recognized in the field as very rough, rough, slightly rough, smooth, polished and slickensided surfaces. The JRC is estimated (Table 1) by comparing the appearance of a discontinuity surface with a standard profile (Barton et al., 1977).

Table 1: Joint roughness profiles with JRC values (Barton and Choubey, 1977)



Groundwater conditions are made by visual observations and accordingly their ratings are estimated. The algebraic sum of these five parameters gives the RMR values for a slope.

The values of all the five parameters are then entered in the rock mass rating system as shown in table 2. Rock mass classes determined from total ratings are given in Table 3.

Table 2: Rock Mass Rating System (after Bieniawski, 1989)

Sl. No	Parameter		Range of values						
1	Strength of intact rock material (MN/m^{-2})	Point load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range- uniaxial compressive test is preferred		
		Uniaxial compressive strength	>200 MPa	100-200 MPa	50-100 MPa	25-50 MPa	5-25 MPa	1-5 MPa	<1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core quality RQD		90-100%	75-90%	50-75%	25-50%	<25%		
	Rating		20	17	13	8	3		
3	Spacing of joints		>2 m	0.6-2 m	200-600 mm	60-200 mm	<60 mm		
	Rating		20	15	10	8	5		

4	Condition of joints		Very rough surface Not continuous No separation. Unweathered wall rock	Slightly rough surfaces Separation < 1 mm; Slightly weathered walls	Slightly rough surface Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge <5 mm thick or Separaion 1-5 mm continuous	Soft gouge <5 mm or Separation >5 mm Continuous
	Rating		30	25	20	10	0
5	Groundwater	Inflow per 10m tunnel length (l/m)	None	<10	10-25	5-125	>125
		(jointwaterpress) / (Major principleσ)	0	<0.1	0.1-0.2	0.2-0.5	>0.5
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing
	Rating		15	10	7	4	

Table 3: Rock mass classes (after Bieniawski, 1989)

Rating	100-81	80-61	60-41	40-21	<20
Class No	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

Slope Mass Rating (SMR)

The SMR is a quantifying method applied on rock masses or rock slope to evaluate the stability conditions of the rock slope. First developed by Romana (1985), it is an empirical equation, modified after the Rock Mass Rating proposed by Bieniawski (1989), by adding factorial adjustment factors for the discontinuity orientation. The slope mass rating is the most comprehensive and widely used technique for rock slope assessment (Umrao et al., 2011).

SMR is obtained from RMR by adding a factorial adjustment factor depending on the joint-slope relationship and adding a factor for the natural slope. Adjustment ratings F1, F2, and F3 for joints are evaluated depending on the joint direction (αj), slope direction (αs), joint angle (βj), and slope angle (βs) (Romana, 1985). The value of F4 is taken corresponding to natural slopes. Here,

- SMR = RMR + (F1 × F2 × F3) + F4F1 depends on the parallelism between strikes of joints and slope faces. Values range from 1.00 to 0.15.
- F2 refers to joint dip angle in the planar mode of failure. Its value ranges from 1.00 to 0.15.
- F3 reflects the relationship between slope face and joint dips.

- F4 denotes the adjustment factor for the method of excavation that has been fixed empirically. The adjustment rating and stability classes are represented in Tables 4 and 5 respectively.

Table 4: SMR rating system (after Romana, 1985)

Case	**Very favourable**	**Favourable**	**Fair**	**Unfavourable**	**Very unfavourable**
Pα_i- α_s Tα_i-α_s- 180° P/T	>30° 0.15	30°-20° 0.40	20°-10° 0.70	10°-5° 0.85	<5° 1.00
P β_j-β_s P F2= T F2	<20° 0.15 1	20°-30° 0.40 1	30°-35° 0.70 1	35°-45° 0.85 1	45° 1.00 1
P β_j-β_s Pβ_i- β_s T F3	>10° <110° 0	10°-0° >110°-120° -6	0 >120° -25	0°-(-10°) -50	<-10° -60
F4	Natural slope +15	Pre- splitting +10	Smooth blasting +8	Regular blasting 0	Deficient blasting -8

P = planar failure	α_s = slope direction	α_j = joint dip direction
T = toppling failure	β_s = slope dip	β_j = joint dip
SMR = RMR + (F1 × F2 × F3) + F4		

Table 5: SMR classes (after Romana, 1985)

Class No	**V**	**IV**	**III**	**II**	**I**
SMR	0-20	21-40	41-60	61-80	81-100
Description	Very poor	Poor	Fair	Good	Very good
Stability	Very unstable	Unstable	Partiallystable	Stable	Fully stable
Failures	Large planar or soil-like	Planar or large wedge	Some joints or many wedges	Some blocks	None
Support	Re-excavation	Extensivecorrective	Systematic	Occasional	None

Kinematic Analysis

Kinematic analysis in landslide studies is a method for analysing potential modes of rock slope failure that may occur due to unfavourable orientation of structural discontinuities (joints, faults, foliations, beddings). The resulting failures may be a planar failure, wedge failure and toppling failure. A planar failure occurs when the failure plane strike parallel or nearly parallel (±20°) to the strike of slope and when dip of failure plane is less than the inclination of slope and greater than the angle of friction along the failure plane. For a wedge failure to occur, the difference between plunge direction of the line of intersection of two discontinuity planes and the direction of inclination of slope face should be less than 20° and the plunge amount of line of intersection of two discontinuity planes should be less than the inclination of slope face but more than the friction angle of slope material. The prerequisite condition for a toppling failure to occur is that, the strike of dominant discontinuity, basal plane of separation and that of the slope face should be parallel or if skewed then at most by 10° to each other (Anbalagan et al., 2007). Graphically, kinematic analysis can be carried out by plotting the discontinuity planes on a circular graph called stereonet or stereogram, based on their orientations in terms of dip direction and inclination of dip. The orientations of the discontinuities are represented on a stereonet in the form of great circles, poles, or dip vectors. Clusters of poles of discontinuity orientations on stereonets are identified by visual investigation or using density contours on stereonets. The direction of a slope failure can be deduced from the stereonet.

The present study utilises RMR, SMR and kinematic analysis to determine the geomechanical influence in the Noklak landslide. Altogether six locations (L1 to L6) were studied. The bedding trends and joints were recorded to identify the possible mode of failure. Fifty rock samples were collected from four locations for determination of the compressive rock strength using the PLT, while the strength of intact rocks in two locations (Table 6) are determined in the field itself using Schmidt hammer (Fig. 2, Fig. 3, Fig. 4). The bedding and joint trends were plotted in Rocscience Dips software (Rocscience Inc., 1998) to construct contour diagram, stereogram and rose diagrams (Fig. 5).

Table 6: Sampling location

Sample Point (L)	Location	Joints measured	Schmidt hammer testreadings	Samples collected
L1	26° 12' 6.75"N 95° 1' 3.60"E	212	--	12
L2	26° 12' 3.48"N 95° 1' 4.61"E	161	--	14
L3	26° 11' 58.74"N 95° 01' 01.64"E	223	--	13
L4	26° 11' 55.28" N 95° 0' 58.90" E	193	--	11
L5	26° 11' 56.67"N 95° 0' 56.14"E	237	10	--
L6	26° 11' 28.69" N 95° 0' 7.38" E	169	19	--

Fig. 2: Schmidt Hammer

Fig. 3: Fractures and joints

Fig. 4: PLT

RESULTS

RMR & SMR

L1

Point load index (PLI) = 0.47MPa, since PLI value is less than 1MPa (Table 1)

Hence using the UCS equation,UCS = 14.4 × 0.47 = 6.76 MPa

RQD = 115- 3.3 × 55 = -66.5

αj (joint direction) = 310, αs (slope direction) = 243

βj (joint angle) = 55, βs (slope angle) = 35

Values are plotted in Table 2.7a

L2

PLI= 0.53 MPa. since PLI value is less than 1MPa (Table 2.1)

UCS = 14.4 × 0.53 = 7.632 MPa, RQD = 115- 3.3 × 60.66 = -85.178

αj (joint direction) = 283, αj s (slope direction) = 262

βj (joint angle) = 80, βs (slope angle) = 36

Values are plotted in Table 2.7a

L3

PLI = 0.51 MPa. since PLI value is less than 1MPa (table 1)

UCS = 14.4 × 0.51 = 7.344 MPa, RQD = 115- 3.3 × 36 =3.8

αj (joint direction) = 238, αs (slope direction) = 252

βj (joint angle) = 86, βs (slope angle) = 31

Values are plotted in Table 7a

Table 7a: SMR System (after Romana 1985)

	L1		**L2**		**L3**	
	Value or Condition	Rating	Value or Condition	Rating	Value or Condition	Rating
1. UCS	6.76 MPa	2	7.63 MPa	2	7.34 MPa	2
2. RQD	-66.5%	3	-85.178%	3	-3.8%	3
3. Spacing of joints	35.69 mm	5	46 mm	5	130 mm	8
4.Condition of joints	Slightly rough surface Separation <1 mm; Highly weathered walls	20	Slightly rough surface Separation <1 mm; Highly weathered walls	20	Slickenside surface; continuous joints; separation <5 mm	10
5.Groundwater condition	Damp	10	Damp	10	Damp	10
RMR	= (1+2+3+4+5)	***40***	= (1+2+3+4+5)	***40***	= (1+2+3+4+5)	***33***
6. $F_1 = \alpha_j - \alpha_s$)	71°	0.15	19°	0.7	-15°	1
7. $F_2 = \beta j - \beta j$	54°	1	80°	1	86°	1
8. $F_3 = \beta_j - \beta_s$ for plane failure where β_s= dip/angle of slope	19°	0	43°	0	51°	0
9. F_4 = Adjustment factor	Pre-splitting	10	Pre-splitting	10	Pre-splitting	10
SMR = *RMR+(F1xF2xF3)+F4*	40 + {0.15 × 1 × 0} + 10	50	40 + {0.7 × 1 × 0} + 10	50	33 + {1 × 1 × 0} + 10	43
10. Class	**III**		**III**		**III**	

L4

PLI= 0.52 MPa. since PLI value is less than 1 MPa (Table 1)

UCS = 14.4 × 0.52 = 7.49 MPa, RQD = 115- 3.3 × 23.5 = 37.45

αj (joint direction) = 74, αs (slope direction) = 260

βj (joint angle) = 77, βs (slope angle) = 34

Values are plotted in Table 7b

L5

Rebound number, R_n = 19.9

Since the lithology in the study area is siltstone, density ρ = 2.6

$UCS = 6.9 \times 10^{(0.16 + 0.0087 \times 19.9 \times 2.6)}$

$= 28.10$ MPa

RQD = 115 - 3.3 × 33 = 6.1

αj (joint direction) = 255, αs (slope direction) = 262

βj (joint angle) = 80, βs (slope angle) = 37

Values are plotted in Table 7b

L6

Rebound number, R_n = 28.84

Since the lithology in the study area is shale, density ρ = 2.15

$UCS = 6.9 \times 10^{(0.16 + 0.0087 \times 28.84 \times 2.15)}$

$= 33.79$ MPa

RQD = 115 - 3.3 × 38 =-10.4

αj (joint direction) = 175, αs (slope direction) = 120

βj (joint angle) = 85, βs (slope angle) = 75

Values are plotted in Table7b

Table 7b: SMR System (after Romana 1985)

	L4		L5		L6	
	Value or Condition	Rating	Value or Condition	Rating	Value or Condition	Rating
1. UCS	7.49 MPa	2	28.10 MPa	2	33.79 MPa	4
2. RQD	37.45%	8	6.1%	3	-10.4%	3
3. Spacing of joints	92.37mm	8	225mm	10	60mm	8
4. Condition of joints	Soft gouge <5 mm or Separation >5 mm Continuous joints	0	Slickenside surface; <5 mm thick separation 1-5 mm; continuous joints	10	Slightly rough surface Separation <1 mm; Highly weathered walls	20

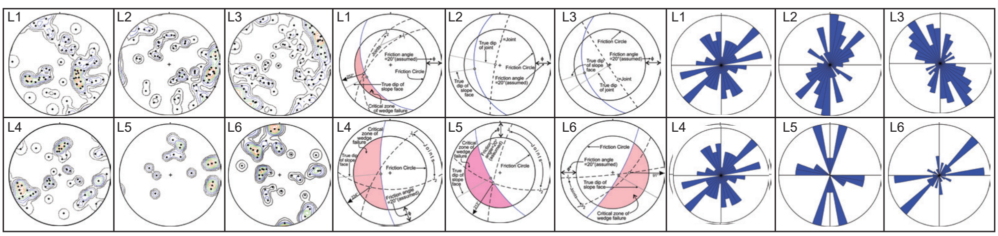
5.Groundwater condition	Completely dry	15	Damp	10	Flowing	0
RMR	= (1+2+3+4+5)	**33**	= (1+2+3+4+5)	**35**	= (1+2+3+4+5)	**35**
6. $F_1 = \alpha_j - \alpha_s$	-192°	1	44°	0.15	54°	0.15
7. $F_2 = \beta_j - \beta_j$	77°	1	80°	1	85°	1
8. $F_3 = \beta_j - \beta_s$ for plane failure where β_s = dip/angle of slope	7°	-6	15°	0	10°	-6
9. F_4 = Adjustment factor	Pre-splitting	10	Pre-splitting	10	Pre-splitting	10
SMR = *RMR+(F1xF2xF3)+F4*	*33 + {1 × 1 × (-6)} + 10*	37	*35 + {0.15 × 1 × 0} + 10*	45	*35 + {0.15 × 1 × -6} + 10*	44.10
10. Class	**IV**		**III**		**III**	

Table 8: SMR class and description of different locations

Sampling Points	Class	Description
L1	III	Fair rock; partially stable slope prone to failure by some joints or many wedges; requires systematic measures
L2	III	Fairrock; partially stable slope prone to failure by some joints or many wedges; requires systematic measures
L3	III	Fairrock; partially stable slope prone to failure by some joints or many wedges; requires systematic measures
L4	IV	Poor rock; unstable slope prone to both planar and wedge failure; requires extensive corrective measures.
L5	III	Fair rock; partially stable slope prone to failure by some joints or many wedges; requires systematic measures
L6	III	Fair rock; partially stable slope prone to failure by some joints or many wedges; requires systematic measures

Kinematic Analysis

Fig. 5: Contour diagrams, Stereographic projection and Rosette generated from rock joints



Results from Stereographic projection and Rose diagram generated from the joints of the study area:

L1

Dominant trends are NE-SW (regional fault and thrust direction) and NNW-SSE antithetic shears (possibility of strike-slip faults). Minor WNW-ESE trend seen is due to synthetic shears. Here, the dominant joint sets J_1 (54° due 314°) and J_2 (41° due 294°) with respect to slope face (35° due 243°) intersect to produce wedge in the direction 252° (Fig. 2.5). The plunge of intersection lines of discontinuity lies within the shaded region and is less than the dip angle of the slope face. This indicates wedge mode of failure according to Hoek and Bray (1981).

L2

The dominant trend is NNE-SSW (most likely regional fault and thrust direction).In slope L2, the principle joint set J (80° due 281°) strike (±19°) with respect to slope face (37° due 262°) (Fig. 2.5).

L3

The dominant trend is NW-SE. The joints in this direction are likely to be coupled with normal fault. In L3, the primary joint set J (86°/237°) strike (±15°) with respect to slope face (35° due 252°) (Fig 5). Both slope L2 and L3 indicate planar failure.

L4

The trend is approximately NNW-SSE. The area may be affected by some joints. However, any displacement along this direction could develop sinistral strike-slip faults. The dominant joint sets J_1 (55° due 181°) and J_2 (67° due 304°) with respect to slope face (34° due 260°) intersect to produce wedge in the direction 234° (Fig. 5). The plunge of intersection lines of discontinuity lies within the shaded region and is less than the dip angle of the slope face indicating wedge mode of failure.

L5

The trend is approximately NNW-SSE. The area may be affected by some joints. However, any displacement along this direction could develop sinistral strike-slip faults. In this location, joint sets J_1 (80° due 254°) and J_2 (80° due 284°) with respect to slope face (37° due 262°) intersects to produce wedge in the direction 213° (Fig. 5). The plunge of intersection lines of discontinuity lies within the shaded region and is less than the dip angle of the slope face indicating wedge mode of failure.

L6

The trends are approximately NE-SW and E-W. Here, joint sets J_1 (85° due 174°) and J_2 (64° due 137°) with respect to slope face (75° due 120°) intersect to produce wedge in the direction 91° (Fig. 5). The plunge of intersection lines of discontinuity lies within the shaded region and is less than the dip angle of the slope face indicating wedge mode of failure.

Table 9: Data description showing the relation between joints and slope

Location	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**
Slope Orientation	35°/243°	37°/262°	35°/252°	34°/260°	37°/262°	75°/120°
Orientation of Principle Joint Sets	J_1=54°/314° J_2=41°/294°	J=80°/281°	J=86°/237°	J_1=55°/181° J_2=67°/304°	J_1=80°/254° J_2=80°/284°	J_1=85°/174° J_2=64°/137°
Failure mode	Wedge	Planar	Planar	Wedge	Wedge	Wedge
Data format	Dip/dip direction					
Magnetic declination = (-ve) 0.433° (west declination of the study area)						

Discussions

Out of the six locations studied, RMR and SMR results of five locations classify the rocks to be normal rock, falling under class III, which is indicative of a partially stable slope that can be prone to failure due to joints (Karaman et al., 2013), while one location is classified under class IV indicating weak rocks. Gravity is the driving force of landslides, but its effectiveness in producing landslides depends on certain other factors. The slope in the study area has very few exposures of well-bedded rocks and is composed mostly of soil and rock debris and hence from a lithological point of view, the slope may be assumed to be fragile and prone to failure. The shales, which are the dominant rock type in the study area, are highly sheared, pulverised and weathered, making them very weak and vulnerable to erosion(Varnes et al., 1978). Structurally, the rocks in the area are dissected by number of joint sets, minor folds and faults. Analysis of rose diagrams and the stereographic projections of the area show at least four dominant joint sets which makes the rocks prone to a planar or wedge type of failure. After a thorough and detailed investigation of the lithology and based on the geo-mechanical parameters, it can be concluded that the slopes in the study area are fairly stable which however are susceptible to failure in the presence of discontinuities such as joints, their distribution and interaction. The slope instability may also have been aggravated due to the presence of weak slope materials and absence of firm rock bedding (Hudson et al., 1997; Hoek et al., 1998). Furthermore, poor drainage and the introduction of water by anthropogenic activities and heavy precipitation may be a triggering factor (Zezere et al., 1998; Wu, 2003). One important factor that might be controlling the slope instability in the area may be attributed to the neo-tectonic activities (Deng et al., 2000; Korup et al., 2007). Study of satellite image shows the presence of a major lineament trending NE-SW, cutting across the Noklak town which trends along the general thrust direction of the region. The Kiamong river has carved its channel along this fault. Along the stream channel, the continual occurrence of slicken sidelends evidence to faulting in the area. The region is traversed by a number of other lineaments. Four lineaments trending parallel to each other, are oriented NW-SE, which is the normal fault setting in the region. The township is dissected by two of these faults. On the northern and southern extremities of the study area, two other prominent lineaments are seen trending parallel to each other along ENE-WSW(Fig. 6), which appear to be hybrid fractures resulting from the complex interplay of stresses.

Fig. 6: Lineament map (Thong, 2019)`

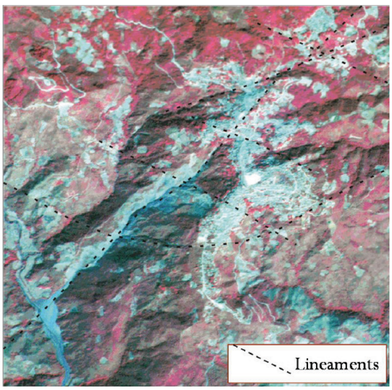


Fig. 7: View of the slide affected area

Mitigation Measures

Noklak town is situated on a tectonically unstable hilly region and developmental activities associated with urbanization imposes great stress on the slopes leading to reduction of the shear strength and resulting in landslides. It is, therefore, necessary to have a proper town planning, develop master plans especially for designing appropriate drainage systems including stormwater drains to ensure the minimal flow of water to the slide affected area. Unscientific and rampant developmental activities including construction of heavy RCC buildings, road cuttings, clearing of vegetative covers for farming etc. in the vicinity of the slide should be restricted. Plantation of well spread, deep-rooted vegetation such as the vetiver grass may impart shear strength to the slope by holding the slope material together. Construction of check dams and embankments should be taken up to reduce toe erosion along the Kiamong river. To reduce the impact on life and properties from the threat of this landslide, public awareness should be generated as well as developing an early warning system.

Conclusion

The present study considered the role of rock mechanics to study the complex landslide at Noklak town. The results show poor rock in only one location and fair rock with the partially stable slope in the other five locations. However, the result also indicates that the presence and distribution of joints would make the slope vulnerable to planar or wedge type of failure. This study concludes that the occurrence of a large amount of rock joints in differing orientations has played a vital role as a causative factor in some cycle of slope movement in this decades-old Noklak landslide. Further investigation to ascertain the role of neotectonics, soil mechanics, etc. is required.

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Quantitative Comparison of Rainfall Thresholds: A Case Study from Kalimpong, India

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Abstract

The increasing frequency of landslides has become a matter of prime concern in the context of Indian Himalayas. Massive losses are reported due to landslides every year, demanding the development of strategies to minimise the impact of such events. Kalimpong in the Darjeeling Himalayas is one among the landslide susceptible towns in India, where rainfall is identified to be the primary triggering factor for the occurrence of landslides. Attempts have been made in the past to develop local-scale rainfall thresholds for the region using different approaches. Among the various methods, empirical methods are observed to be the simplest approach in predicting landslides. The procedure includes finding the relationship between rainfall and landslides happened in the past to predict the possible occurrence of landslides in future. In this work, three different empirical relationships derived for the region are compared to find the best-suited method and to testify their applicability in an operational Landslide Early Warning System(LEWS). The Event Duration thresholds defined using an algorithm based approach is found to be performing better than the other two models considered in the analysis. It is observed that the empirical relationships have to be improved conceptually to be used as a tool for LEWS.

Keywords: Landslides, Rainfall Thresholds, LEWS

Introduction

Rainfall induced landslides are claiming several lives and causing large scale destructions in Indian Himalayas. The increase in population and urbanisation of hilly areas are making the scenario worse by increasing the fatalities. Kalimpong town is located in the Darjeeling Himalayas, in West Bengal State (India) and is highly affected by landslide hazards. During monsoon seasons every year, landslides are creating havoc in the region

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by disrupting communication and transportation facilities and damaging houses and agricultural lands. As the people of the locale are depending on agriculture and tourism as its major income sources, landslides and associated losses are directly affecting the economy of the town. Transportation facilities are often blocked during monsoon causing difficulties to both locals and tourists.

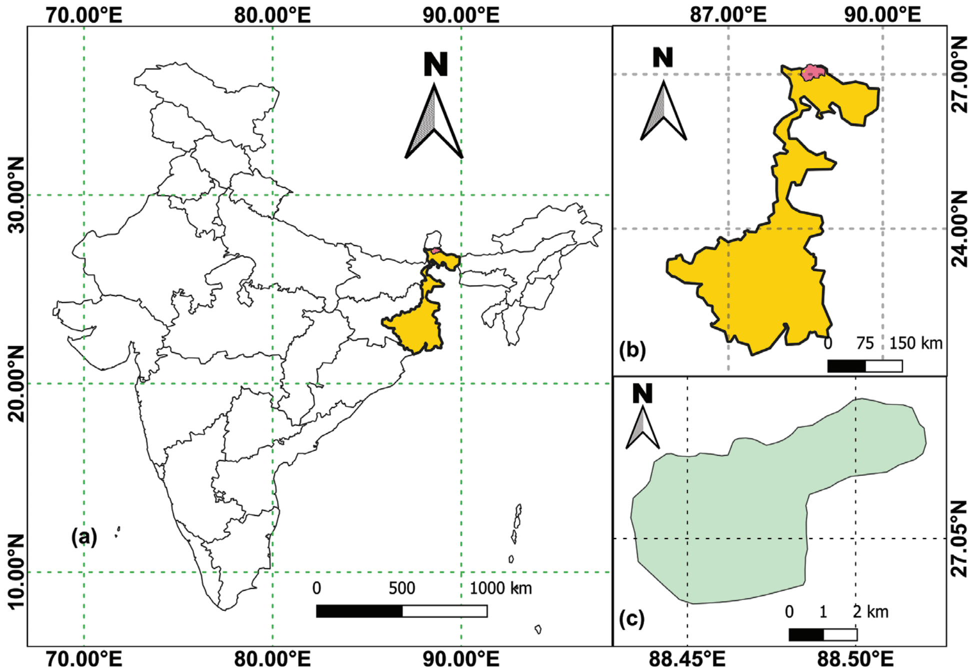
Continuous precipitation and infiltration increase the moisture content of the soil. This in turn increased pore water pressure and decreases the shear strength of soil, which is attributed as the reason for slope failure due to rainfall. But the soil properties and slope conditions are often complicated, as these parameters vary greatly within a short distance and time. The spatial and temporal variation of in situ parameters makes the detailed understanding of physical processes complicated and hence prediction of landslides based on physical parameters is hence suitable for detailed site-specific studies. A widely accepted approach is to obtain the relationship of several rainfall parameters (Event rainfall, Intensity and Duration) which resulted in landslides in the past to predict the future landslides. The thresholds are termed as Empirical thresholds, as it derives an empirical relationship which differentiates the rainfall events which can trigger landslides from those which cannot trigger landslides. In other words, thresholds define a critical condition above which landslides are likely to occur.

In this study, three such thresholds defined for Kalimpong town, one based on Intensity-Duration relationship, one based on intensity-duration relationship, one based on antecedent rainfall conditions and a third one based on the event-duration relationship are being evaluated. The objective is to find the best model among the three, which predicts the possible occurrence of a landslide in the study area.

Study Area

Kalimpong town is a part of Kalimpong district in the state of West Bengal in India (Fig. 3.1). The town is located between rivers Relli and Teesta and has altitudes as high as 1,247 m (Dikshit and Satyam, 2018). The region is characterised by steep and very steep slopes which become unstable due to high precipitation in the monsoons. Due to poor lithological quality and erosion by river Teesta and its tributaries, most of the western slopes in this region are destabilised (Dikshit and Satyam, 2018). Highly weathered chlorite schist, phyllite and phyllitic quartzite of the Daling group contribute to the geology of the region (Sumantra, 2016). The rocks are usually covered by a thin to thick heterogeneous debris material (GSI Report, 2016). The topsoils are mostly red in colour with occasional dark soils (Dikshit and Satyam, 2018) due to the presence of phyllites and schists. The particle size ranges from coarse to rocky as the elevation increases.

Fig. 3.1: Location Map of Kalimpong (a) India; (b) West Bengal; (c) Kalimpong Town



The region is drained by a system of streams which are the tributaries of rivers Relli and Teesta. The smaller order streams join together and become higher-order streams. These untrained rivulets often called as jhoras in the locale have increased the landslides in the area. Regions near to the major jhoras are suffering from continuous sinking during the monsoons(Dikshit and Satyam 2019). The population in this hilly area is increasing and this demands more construction activities and toe modifications of hills. These anthropogenic activities have also contributed to the increased number of landslides in the region.

Rainfall Thresholds

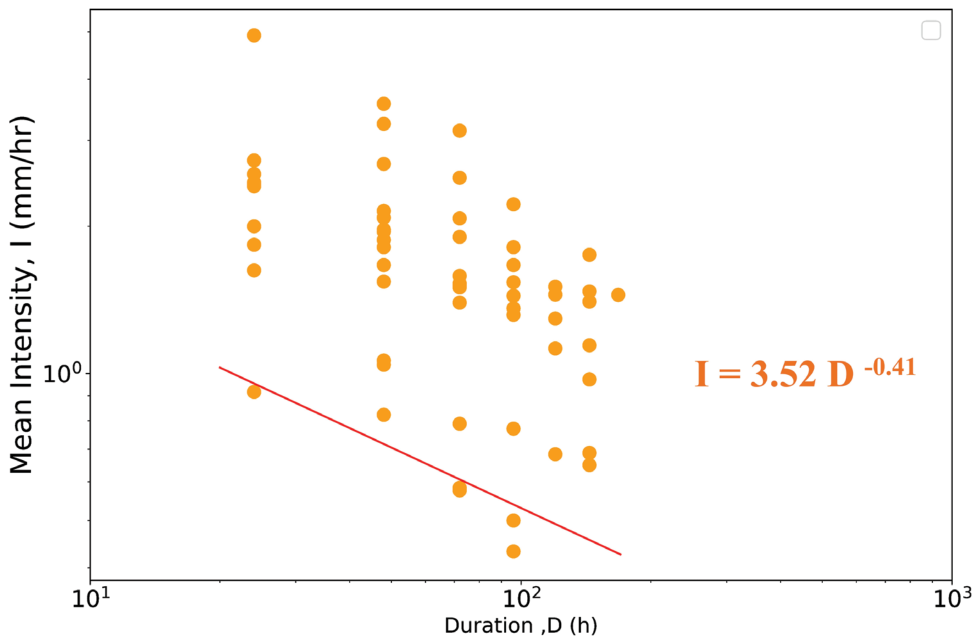
Three different thresholds established for the region is considered in this study for quantitative comparison. The first threshold considered was Intensity-Duration (ID) Thresholds prepared using a catalogue of 61 landslide events that happened in the region from 2010-2016 (Figure 2) (Dikshit and Satyam, 2017). The rainfall associated with each landslide event was found using a frequentist approach and a threshold was defined for the region as

$$I = 3.52D^{-0.41} \qquad [1]$$

where I is the average intensity associated with the rainfall event intensity in mm/h

D is the duration of event in hours calculated from the start of rainfall till the occurrence of landslide.

Fig. 3.2: Intensity- Duration Thresholds (Dikshit and Satyam 2017)



An analysis based on antecedent rainfall was also conducted for the study are and thresholds were defined as rainfall of 88.37 mm over a period of 10 days and rainfall of 133.5 mm over a period of 20 days are potent enough to trigger landslides in the region.

The use of Intensity (I) as a variable to define the rainfall thresholds is criticized considering the variables measure independent quantities while determining functional relationships. This assumption is violated when searching for a relationship between the rainfall duration *D*, and the rainfall means intensity I because the rainfall means intensity depends on the rainfall duration, through the cumulated rainfall (E). For this reason, Event-Duration (ED) thresholds are widely followed in the recent literature (Teja, Dikshit and Satyam, 2019; Melillo et al., 2018; Zhang and Han, 2017) apart from the classical Intensity-Duration approach. The empirical relationship between cumulated rainfall event and duration was derived for the area using an algorithm based approach, named CTRL-T. The approach is more precise in nature as it considers the location of the rain gauge, its altitude and by comparing the location of landslide events, the algorithm reconstructs the rainfall event associated with it. The events are discarded if the landslide events are not occurring within a user-defined circumference around the locations of available rain gauges. The user can prescribe a lag time also, beyond which a rainfall event is not potent enough to trigger a landslide. 29 landslide events were considered by the algorithm for the analysis, which came within 15 km radius around the rain gauge considered for analysis. Statistical bootstrapping was used to find the uncertainty associated with threshold and with 5 per cent exceedance probability, event-duration threshold for Kalimpong was derived as

$$E = (4.2 \pm 1.3)D^{(0.56 \pm 0.05)} \quad [2]$$

where E is the cumulated rainfall calculated from the start of rainfall event till the day of the landslide in mm and D is the duration in hours. These three thresholds were considered for the quantitative comparison by using rainfall and landslide data of the years 2016 and 2017.

Results and Discussions

The results of all three models were simulated using the rainfall data of 2016-2017. The rainfall data was collected from the rain gauge maintained by Save The Hills at Tirpai, Kalimpong (“Save The Hills Blog”). Details of landslides were collected from the Geological Survey of India Reports, print media, field investigations (Dikshit and Satyam 2017) and field monitoring (Dikshit and Satyam, 2019).

Based on the occurrence or non-occurrence of landslides, it is evaluated whether the model predicted correct/incorrect results. The results can be of four types (Table 1). By using the conventional approach of the confusion matrix, the results are classified as True Positives (TP), True Negatives (TN), False Positives (FP) and False Negatives (FN). TP are assigned for days on which landslides occurred as predicted by the model. True Negatives are assigned to days without landslides as correctly predicted by the model. False Positives are used when model issue an unsafe condition and landslides did not take place. FN condition is used to identify days on which landslides occurred but the model failed to predict the landslide.

Table 3.1: Classification of Model Predictions

Observations		TP	FP	FN	TN
ID	(Dikshit and Satyam 2017)	8	98	7	618
Antecedent	(Dikshit and Satyam 2018)	15	206	0	510
ED	(Teja, Dikshit, and Satyam 2019)	8	75	7	641

Some statistical attributes were derived using these four outputs, which quantifies the performance of each model as tabulated in Table 3.2.

Table 3.2: Statistical Comparison of Rainfall Thresholds

Statistical Attributes	ID	Antecedent rainfall	ED
	(Dikshit and Satyam 2017)	(Dikshit and Satyam 2018)	(Teja, Dikshit, and Satyam 2019)
Sensitivity = TP / (TP + FN)	0.53	1.00	0.53
Specificity = TN / (FP + TN)	0.86	0.71	0.90
Efficiency = (TP + TN) / (TP + FP + FN + TN)	0.86	0.72	0.89
Likelihood ratio = Sensitivity / (1 – Specificity)	3.90	3.48	5.09

It can be observed that out of the 3 models, only thresholds based on antecedent rainfall was able to predict all the landslide events correctly. ID and ED thresholds predicted 7 out of 8 shallow landslides occurred in 2016, but failed to forecast the slow movements happened in 2017. These models consider the effect of immediate preceding effects only and hence the long term effect of rainfall the resultant pore pressure generation is not considered. While in the case of antecedent rainfall thresholds, it forecasted all the landslide events during the validation time, but the number of false alarms is very high in this case. The term sensitivity measures the ratio of occurrences of landslides which are correctly identified. It is observed that the antecedent rainfall thresholds are having the highest value of sensitivity, i.e. 1. Similarly, the term specificity measures the days without landslides, which are correctly predicted by the model. Specificity is the maximum for the ED threshold and is the minimum for Antecedent rainfall thresholds. For a model to be used as a part of LEWS, it should have both sensitivity and specificity as 1. Hence it is important to analyze the efficiency and likelihood ratio of the models, which count the overall performance. Efficiency quantifies the ratio of correct predictions with respect to the total number of days. The ED thresholds are having a maximum efficiency of 89 Per cent. In case of landslide, predictions accounted for each day, the number of true negatives is usually of a higher order than the other variables. Hence the efficiency values are obtained as values close to one and the different models will have comparable efficiency values. To overcome this disadvantage, we use the term likelihood ratio, which is the ratio of sensitivity and (1-specificity). As this parameter considers the effect of sensitivity and specificity in a single value, this is a more reliable parameter for comparison. In this study, ED threshold is having the highest Likelihood ratio. Antecedent rainfall thresholds can be improvised by methods to limit the number of false alarms and can be used as a part of LEWS along with a rainfall forecasting system.

Conclusion

A comparative analysis was carried out to determine the suitability of different rainfall thresholds defined for Kalimpong town in West Bengal. For the comparison purpose, a dataset of 2 years was used and three different models were quantitatively analysed and the statistical attributes were compared to obtain the best-suited model among them. The main findings from the study can be summarised as:

- Intensity-Duration and Event-Duration thresholds are useful for the prediction of shallow landslide events but they fail in forecasting the deep-seated movements which are the effect of long term rainfall.
- Antecedent Rainfall thresholds are correctly predicting both rapid and slow movements in the study area, but the model produces a very high number of false alarms, which reduces the overall performance of the model.
- The Event-Duration threshold is giving better performance among the models considered with an efficiency of 89 per cent likelihood ratio of 5.09.
- The performance of the models can be conceptually improved to reduce the number of false alarms to be used as a part of LEWS.

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Need of National Landslide Risk Management Strategy for Reducing Landslide Risk in India

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Abstract

National Disaster Management Authority (NDMA), is the apex body for the disaster management in India under the Chairmanship of the Hon'ble Prime Minister, is mandated to lay down the policies, plans and guidelines for disaster management to ensure a timely and effective response to disasters. India is vulnerable to different landslides which cause significant destruction in terms of loss of lives and property. As per GSI, about 0.42 million km² covering nearly 12.6 per cent of the land area of our country is prone to landslide hazards. At present, no Ministry/Department of the Government of India (GoI)has formulated a national level landslide risk management strategy. In order to fill in this gap, NDMA formulated National Landslide Risk Management Strategy to adopt a holistic approach for mainstreaming landslide risk reduction, besides strengthening of the State machinery and providing all necessary technical support to the concerned States and Union Territories (UT's) for addressing landslide problem in a sustained manner. In this regard, NDMA had constituted a Task Force of experts from diverse backgrounds for the formulation of a national and local level strategy for landslide risk reduction. The strategy is fulfilling the fifth target of Sendai Framework for Disaster Risk Reduction (2015-30) i.e., Substantially increase the number of countries with national and local disaster risk reduction strategies by 2020. The strategy document was released in the 15th Formation Day of NDMA on 27 September 2019; addresses all the components of landslide disaster risk reduction and management such as hazard mapping, monitoring and early warning system, awareness programmes, capacity building and training, regulations and policies, stabilisation and mitigation of landslide, etc. The strategy document envisages specific recommendations for the concerned Nodal Agency, Ministries/Departments, States and other stakeholders, so as to avert or reduce the impact of future landslide calamities.

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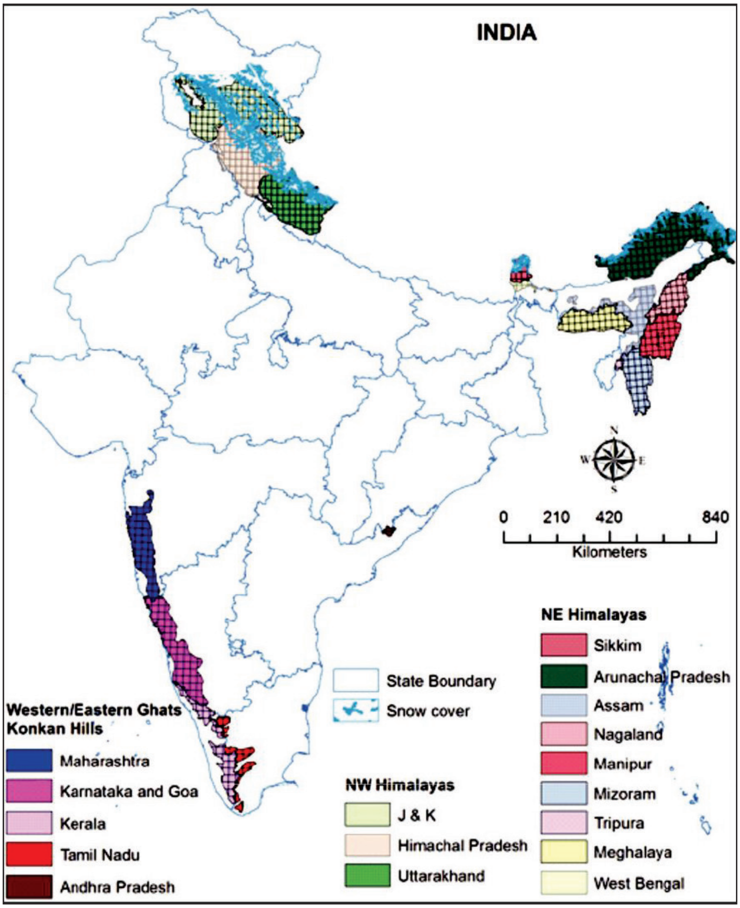
Keywords: Landslide, Risk, Mapping, Early Warning System (EWS), Awareness; Capacity Building, rainfall, seismicity.

Introduction

India is vulnerable to different types of landslides which cause significant destruction in terms of loss of lives and property. As per GSI, about 0.42 million km^2 covering nearly 12.6 per cent of land area of our country is prone to landslide hazards (Fig. 4.1). The mountainous region of the North-Western Himalayas, the Sub-Himalayan terrain of the North-East, the Western and Eastern Ghats are prone to landslides.

Fig. 4.1: Major landslide prone areas of India (0.42 million km^2)



Landslide hazards rank high among the hydro-geological hazards because they pose a threat to life and livelihood ranging from disruptions of normal activities to widespread loss of life, property and destruction in large parts of the mountainous region of India. Himalayan and other hilly regions of India are affected by landslides and landmass movement activities. During the monsoon, these areas witness frequent landslides. Some of the major recent incidents are Kerala (2018), Himachal Pradesh (2018), Uttarakhand (2018), Tamenglong-Manipur (2018), Kalikhola, Manipur (June 2017); Laptap, Pampare-Arunachal Pradesh (July 2017); Malpa, Uttarakhand (August 2017); Kotropi, Himachal Pradesh (August 2017); Malin, Pune (July 2014); Mirik, West Bengal (June 2015), etc. causing huge loss to life and property. Most of the landslides occur due to heavy rainfall. Majority of landslide-prone areas are located in the earthquake-prone seismic Zone-IV and V. Thus these areas are also prone to earthquake-triggered landslides e.g., Sikkim Earthquake (2011), Kashmir Earthquake (2005), Chamoli Earthquake (1999), Uttarkashi Earthquake (1991), etc. In recent years, the incidences of landslides have increased due to extreme weather events, environmental degradation due to human interference and other anthropogenic activities resulting in heavy losses of human lives, livestock and property.

As per the Disaster Management Act, 2005 the National Disaster Management Authority (NDMA), a statutory and apex body under the Chairmanship of the Prime Minister, is mandated to lay down the policies, plans and guidelines for disaster management to ensure a timely and effective response to disasters. In June 2009, NDMA released the National Disaster Management Guidelines on Management of Landslides and Snow Avalanches formulated in consultation with the Nodal Ministry/Agency (MoM/GSI) and other core group members from concerned Central, State departments and academia, laying down national policy for the management of landslide related hazards in the country.

NDMA constituted a Task Force of experts for the formulation of National Landslide Risk Management Strategy. Task Force comprising of experts from diverse backgrounds in the relevant fields to identify problem/gaps, reviews of past work, recommendations, implementation strategy, financial implications, monitoring mechanisms etc. was constituted to formulate the strategy. The Task Force was divided into six Sub-Groups as under:

- Generation of User-FriendlyLandslide Hazard Map
- Development of LandslideMonitoring and Early Warning System
- Awareness Programmes
- Capacity Building and Training of stakeholders
- Preparation of Mountain ZoneRegulations & Policies

- Stabilization and Mitigation of landslides and Creation of Special Purpose Vehicle (SPV) for Landslide Management

Discussion

The strategy clearly brings out the message for the need to strengthen and mainstream landslide disaster preparedness, mitigation, response and relief mechanism through mapping, early warning system (EWS), awareness generation, capacity building, formulation of mountain zone regulations/policies and mitigation of problematic landslides. The important points of six sub-groups are highlighted as follow:

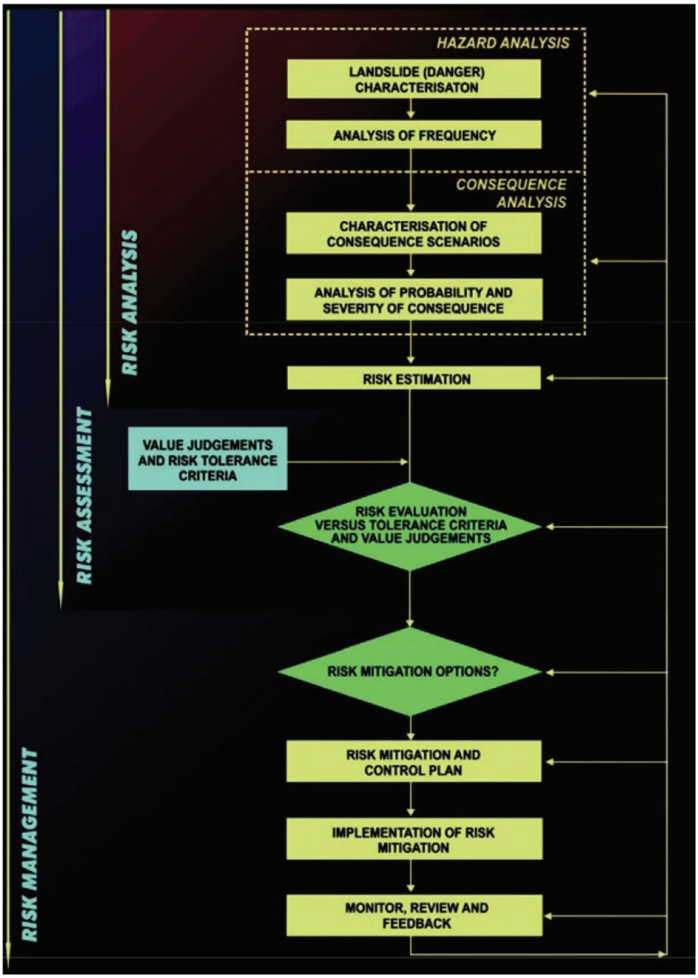
I. Generation of User-Friendly Landslide Hazard Maps

It covers aspects of reliability and validation of landslide zoning maps in the Indian scenario and proposes a future plan of activities for landslide zoning. It recommends Landslide Hazard Zonation maps to be prepared at the macro scale (1:50,000/25,000) and meso level (1:10,000). It focuses on the use of advanced state-of-the-art tools such as Unmanned Aerial Vehicle (UAV), Terrestrial Laser Scanner, and very high-resolution Earth Observation (EO) data. A suitable monitoring mechanism and quality checking option may be established at all levels to ensure the quality of deliverables.

- **Landslide Zoning** is the division of hill or mountainous areas into homogeneous spatial areas/slope according to their degrees of actual or potential landslide susceptibility, hazard or risk.
- **Landslide Susceptibility Zoning (LSZ)** uses an inventory of past landslide incidences together with an assessment or prediction of the spatial areas/slope with a likelihood of landslides in the future. Susceptibility zoning thus involves the spatial distribution and rating of the terrain units according to their propensity to produce landslides. This is dependent on the topography, geology, geotechnical properties, climate, vegetation and anthropogenic factors such as development and clearing of vegetation.
- **Landslide Hazard Zoning (LHZ)** uses the landslide susceptibility maps and assigns an estimated frequency (i.e. annual probability) to the potential landslides of a certain magnitude.
- **Landslide Risk Zoning (LRZ)** depends on the elements at risk, their temporal-spatial probability (or exposure) and vulnerability and is the ultimate aim of any zoning exercise. Administrator/Planners/Insurers are mostly interested in risk maps for their accurate planning and allocation of resources, etc. For new areas under planned developments, an assessment will have to be made of these factors. For areas with existing development, it should be recognised that risks may change with additional development and thus, risk maps should be updated on a regular basis. Therefore,

landslide zoning is always to be construed and viewed as an integral part of the broader landslide risk management framework (Fig. 4.2), proposed by Fell et al. (2005), which has widely been accepted internationally.

Fig. 4.2: Landslide Risk Management Framework (Fell et al., 2005)



In India, we must make sincere and all-out attempts to convert our susceptibility maps into true hazard and risk maps following the above-mentioned internationally-accepted methodologies. However, landslide zoning is being carried out for specific purposes and for regional, local and site-specific planning as well as safe and optimal use of landmass. The outputs are usually in the form of one or more of the following: landslide inventory map; landslide susceptibility map; landslide hazard and risk maps; and associated reports.

a. Problem/gaps

- Landslide zoning maps so far available in India are mostly LSZ maps; however, in most of the cases, they are termed as LHZ maps despite not having any connotation about the magnitude and temporal predictions.
- The LSZ maps prepared till 2014 in India are concerned only to important route corridors and at some discrete locations (which have witnessed damage due to landslides) in some highly landslide prone States.
- Single Seamless state-wise/ district-wise landslide zonation maps are mostly not available for landslide prone northern, northeastern states and for Eastern and Western Ghats regions, which, however, this has recently been taken care of on regional/ medium scale (1:50,000) by GSI's National Landslide Susceptibility Mapping (NLSM) programme since 2014-15.
- In India, LSZ maps for the same area have also been created by different workers of different organisations following different methodologies. In such cases, which of the LSZ map is to be followed for mitigation measures is not clear to the users.
- Majority of the existing LSZ Maps are lacking details of the devastating landslide events of the past. Therefore, landslide incidence map prepared from multi-temporal and event-based sources along with its detailed geo-parametric attributes needs to be measured while ranking and weighting the thematic geo-factors for preparation of LSZ maps.
- Most of the available LSZ maps are on 1:50,000 scale because of its easy availability of source datasets and methods. But for effective developmental planning, its utility has some limitations. Moreover, on scale 1:50,000, active landslide zones of smaller dimensions having sizes of 50 m × 50 m appear as a dot (1 mm × 1 mm) on 1:50,000 scale map.
- Slope cutting and blasting activity for construction and widening of hill roads are triggering many landslides, which are in many cases merely 10-30 m wide. Such small landslides are often life-threatening on hill roads and are difficult to depict on 1:50,000 scale LSZ maps.
- From meso/large scale (1:10,000) analysis, reliance on more number of field-based inputs and analytically-determined attributes of slope forming material are needed, which are not only time consuming but also costly in nature and cannot

be implemented for large areas. Therefore, areas/sectors undertaken for 1:10,000 (meso) scale LSZ must be prioritised based on proper justification and evaluation of its risk scenarios.

- Scope of finding linkages of structural mitigation measures with meso/local scale LSZ, though difficult may be sought, so that more direct use of LSZ maps can be justified, for which some research projects can also be launched by Department of Science & Technology (DST).
- Most of the existing LSZ and landslide susceptibility maps are lacking administrative boundaries such as district, Tehsil, block and village boundaries superposed on hazard zones.
- Drainage divides are rarely shown on LSZ maps and only little drainage are shown. Hence, lack of drainage divides in general and watershed boundaries, in particular, make it almost impossible to integrate landslide mitigation measures with ongoing watershed development projects.
- Names of the elements at risk (viz. roads, canals, railway line tunnels, bridges) falling within the high, very high and severe hazard zones are missing in the existing LSZ maps.
- Existing stability measures are neither shown not mentioned in the presently available LSZ maps because of scale constraints.
- No detailed landslide inventory created on the basis of 1:10,000 scale macro-level LSZ maps is available for the formulation of landslide mitigations planning at district, Tehsil, block and village level. Therefore, landslide inventory mapping needs to be carried out at the highest possible level of larger scales (preferably 1:10,000 or larger), so that none of the smaller landslides are missed.
- Landslide Susceptibility Management (LSM) maps are not available for all areas for which LSZ maps are available. Even the available Landslide Susceptibility Management (LSM) maps are lacking site-specific structural and non-structural mitigation measures since most of such LSZ maps are on 1:50,000 scale.
- The mitigation measures recommended in the existing LSM maps are generalised ones, such as “afforestation” and “biotechnical measures” without any mention of the particular varieties of the fast-growing trees and useful grasses to be grown or list of biotechnical measures to be taken for stabilising the hill slope.
- The available LSM maps address the anthropogenic intervention (in landslide susceptible zones) very casually by suggesting measures such as “avoid further construction”, etc. This makes it difficult for the authorities to ensure strict adherence to land use regulations such as a complete ban on construction activity in a landslide hazard-prone area.

- Existing LHM maps do not address the crucial aspects of overloading and or undercutting of hill slope due to anthropogenic activities and therefore, provide no clear guidelines for removal of those manmade constructions in particular which are overloading or undercutting the hill slope or blocking, diverting or narrowing the natural drainage courses.

b. Suggestive Interventions

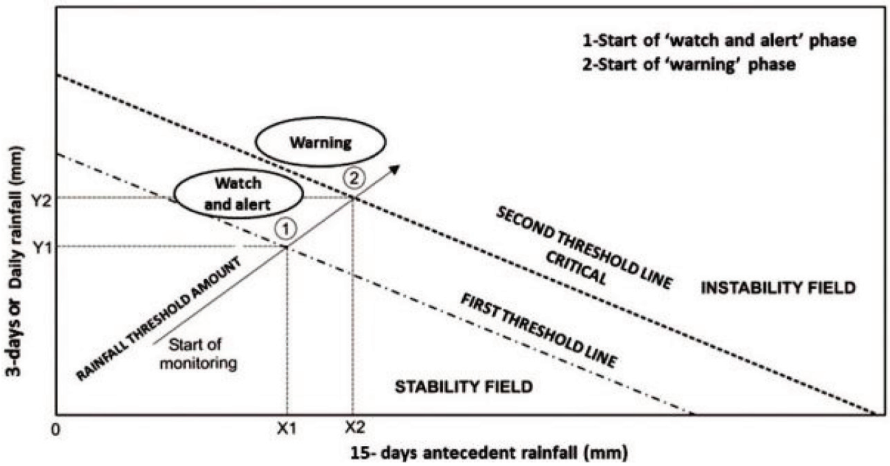
- Collection and cataloguing of all the available Landslide Hazard Zonation (LHZ) and Susceptibility Zonation (LSZ) maps, reports and atlases created by various state and central government departments, institutions and agencies, etc.
- Creation of meso level LHZ Maps on 1:10,000 scale in order to cater to the requirements of Landslide Hazard Management planning at District, Tehsil and Block level.
- Meso level LHZ Maps on 1:10,000 Scale of the already prioritised sectors should be created using very high-resolution remote sensing data, detailed field input, GPS, LiDAR and GIS techniques.
- Use of web-based and app-based dissemination tools for the preparation of maps for common use not only by the administrators but also by the community, tourists, etc.
- On macro scale (1:50,000/25,000), GSI's terrain-specific methodology followed in NLSM project can be considered as an optimal methodology pertinent to that scale. NLSM maps need to be made available in mobile phones through app-based platforms.
- Sectors for meso/large scale (1:10,000) landslide zonation preferably be chosen from the areas where previously created LHZ outputs by different agencies are available including those of NLSM, so that basic landslide and thematic database on the macro scale can be used as base maps for this study.

II. Development of Landslide Monitoring and Early Warning System

Landslides are often triggered by intense rainfall or earthquake and it is observed that seismic high hazard zones and high rainfall areas coincide with high landslide hazard zones. Therefore, for early warning of landslides in India, it is pertinent to explore both the triggering factors i.e. precipitation and seismicity.

The warning can be issued based on the actual threshold calculated with rainfall forecast. As the rainfall is dynamic, so also RT/I-D and based on exceedance of threshold values corresponding to landslide phenomena in the past, the values can be interpreted in terms of severity. In order to illustrate the above concept, methodology, as envisaged by GSI, can be cited (Fig. 4.3).

Fig. 4.3: Schematic diagram that can be used to issue a warning of rainfall-induced landslides based on rainfall threshold



During 'watch and alert' phase one has to be watchful and look for further information or if the precipitation increases then one should take action appropriate for 'warning' phase. During the warning phase, stakeholders should be ready for evacuation in high or very high hazard zones. In fact, after the 'watch and alert' warning the people should be on the alert, and start looking for signs of instability to evacuate.

This sub-group strategy highlights the past work, best practices and present status in the field of Landslide Early Warning System (LEWS), rainfall threshold-based modelling, ground-based wireless instrumentation and real-time monitoring system for landslide prediction, an earthquake triggered a landslide, monitoring mechanism of landslides and gap areas in landslide monitoring and development of early warning system. For future prospects, the technical recommendation for developing and implementing rainfall thresholds, Numerical Weather Prediction (NWP), Automatic Rain Gauges, Wireless Sensor Network (WSN), Micro-Electro-Mechanical Sensors (MEMS), etc. have been included.

a. Problem/gaps

In Indian Himalayas, the poor network of weather stations and lack of high elevation rain gauges and the collection of useful data that can help to establish meaningful relationships. Furthermore, accurate dates of landslides are seldom available due to sparsely population of the region and lack of media and official reporting of such events, although such reporting has improved in recent years.

- Well validated rainfall-threshold model is yet to be developed for all critical regions. For building rainfall threshold-based model intensity-duration (ID) based threshold, date of past landslide events and corresponding representative daily/hourly rainfall data are required. In India, except for some cases, these datasets are not easily available for the most part of the mountainous regions.
- Threshold model itself does not provide information on the spatial occurrence of potential landslides; it has to be combined with landslide susceptibility to forecast Spatio-temporal initiation of landslides.
- Information on the precise time of a landslide based on instrumentation and real-time monitoring is mostly lacking.
- In India, safe shelter and alternate route maps for landslide hazard are often not available. These maps are to be prepared for important road sections and settlements.
- Another important aspect that makes early warning ineffective is the lack of public awareness. This tends to reduce the risk by increasing awareness among the public with an aim to timely response to the warning when the disaster strikes.
- Communication of warning or risk to all concerned stake holders remains a challenge as most of the hilly area population either remains isolated, unreachable, non-responsive due to remoteness of the region or lack of awareness. Therefore, a multimedia approach involving internet portal, SMS, social media, radio and print media is required.
- Access to secondary high-quality rainfall prediction data, LHZ maps, and geotechnical data developed by other stakeholders at one platform.
- Regulation and enforcement promoting monitoring of potential/existing landslides that pose risk to life, economy and environment to large extents are weak.

b. Suggestive Interventions

Rainfall Threshold-based Landslide Early warning System (RT-LEWS)

- Database on rainfall derived from satellite and ground-based observation need to be compiled and analysed to understand variability in a region vis-à-vis landslides.
- Road/railroad maintenance records of Border Road Organisation (BRO) and railway department provide information of date and spatial distribution of landslides in the form of debris accumulated on the road but is restricted to only defined road/railway sectors. The type of data available with them also requires intense field validation before making them useable for threshold modelling.
- Compilation of landslide database with information on typology, location, date and time of occurrence. High-resolution satellite images need to be used to prepare the spatial database with good accuracy.

- Development of rainfall threshold models (I-D and antecedent rainfall based) using available information (rainfall and landslide) from IMD, BRO and other sources for regional and local level LEWS. It is envisaged to use I-D and RT-based models using data mining and statistical approaches as demonstrated by IIRS, CBRI and GSI.
- Rainfall prediction by the Numerical Weather Prediction (NWP) models to increase the lead time of early warning. The NWP models can provide very accurate rainfall forecasts 72 hours in advance over the mountainous regions.
- In order to address landslides induced by extremely localized high precipitation events known as **"Cloud Burst"**, it is desirable to increase the density of automated rain gauges (ARGs) or automatic weathers stations (AWS) in hilly regions with appropriate arrangement and analyse it on real-time hourly data or data at minute's interval using DART and I-D model.
- Wireless networking of all landslide monitoring stations and the establishment of real-time rainfall monitoring control room. Also, the development of early warning communication mechanism.
- Implementation of rainfall based landslide early warning system for regional and local use i.e., Alarm/broadcasting system for traffic control on hill roads/highways during monsoon seasons and community use in hill habitats for landslide risk reduction.
- The threshold model, as established for different regions, can be used to calculate the probability of landslides based on predicted rainfall and its accuracy would be as good as rainfall prediction accuracy which is improving significantly due to better weather forecast models. Rainfall forecast can improve significantly by using Doppler Weather Radar (DWR), which can further help the landslide prediction and early warning.

Ground Instrument based landslide early warning system (GI-LEWS)

- Selection of problematic severe landslides for instrumentation in different parts of hill states.
- Preliminary deformation monitoring using GNSS.
- Investigation of landslides and finalisation of the scheme of landslide instrumentation using cost-effective smart techniques including space technology.
- Wireless sensor network (WSN) based instrumentation and real-time monitoring of landslides.
- Greater emphasis should be on MEMS-based sensors (e.g. accelerometer, soil moisture sensor, force sensor, tilt sensor, etc.).
- Periodic data capture and analysis to develop multi-parametric threshold models for landslide early warning.

- Validation of landslide early warning thresholds and models.
- Development of early warning communication mechanism.
- Implementation of instrumentation based landslide early warning system for societal use.

Seismicity induced landslide EWS (SI-LEWS)

- Selection of study area and compilation of seismic data and early records of Seismic Induced Landslide (SIL).
- Preparation of surface geological map and good quality slope map from DEM.
- Geotechnical characterisation of surface geological materials.
- SIL modelling for simulated events and result validation.
- Deployment of MEMS-based seismometers and accelerometers for real-time warning.

III. Awareness Programmes

The role of concerned State/UT's authorities and local communities are essential not only in the preparedness and mitigation phases of disaster management but, also in the emergency situations during the event. Awareness and capacity development programmes will be successful if the involvement of local communities and authorities such as District Administration, Panchayati Raj Institutions and local communities are maximized.

The sub-group strategy spells out the need of awareness programmes, review of past work and best practices, identification of gaps, as well as recommendations and implementation strategies. It aims towards a culture of awareness generation and preparedness; so that people in the society become alert and aware in case of an emergency or take some preventive measures before the disaster strikes. A participatory approach has been defined so that each section of the community is involved in the awareness drive. Since the community is the first to confront the disaster before any aid reaches them, a mechanism of awareness is framed to involve and educate the community.

a. Problem/gaps

Bringing all the stakeholders of society together helps to ensure the durability and the expansion of landslide risk reduction in society and also other geographical areas by involving the local people considered as catalysts of change. The active engagement at the global level, linking and integrating their best practices by supporting technical experts tend to strengthen the knowledge dissemination channels on landslide risk mitigation and encourages further awareness among all the different stakeholders on the landslide risk situation. Subsequently, disaster risk adaptation mechanisms can be expanded swiftly and more easily to other types of risks.

- Classification of the States which are prone to landslides according to severity.
- Need to study the socio-economic profile of the communities residing in these areas.
- Awareness programmes and campaigns are to be conducted on regular basis. A major drawback of the system is that awareness programmes do not reach the community vulnerable to the disaster. A comprehensive awareness outreach is to be established.

b. Suggestive Interventions

- Involvement of local masses.
- Enhancement of education focusing upon youth especially.
- Involvement of educated mass for creating awareness amongst local people and school children.
- Promotion of the latest technology and techniques.
- Creation of common signage for landslides prone area across the country.
- Toll-free number for landslide reporting.
- Use of posters and hoardings.
- Use of Disaster Preparedness and Disaster Response Apps.

IV. Capacity Building and Training of Stakeholders

In India, the need for Capacity Building and Training of the stakeholders in landslide risk management was realised not long ago. The realisation came after two tragic events of Okhimath and Malpa landslides during in August 1998.

This sub-Group strategy highlights the past work, gaps, implementation strategy, financial implications and monitoring mechanism for capacity building and training in landslides. The key recommendations include a nationwide Training Need Assessment (TNA) in Landslide Risk Management and Inclusion of new technology inputs for capacity building and training programs on landslide DRR. It also focuses on identifying targets group for training on landslide DRR and most importantly, strengthening the response framework through capacity building and training of vulnerable communities at the grassroot level.

a. Problem/gaps

- A comprehensive training needs assessment at various levels of administrative hierarchy viz. National, State, District, Tehsil, Block and Village level needs to be conducted in all landslide-prone states. Different training modules should be prepared for each level, and the frequency of training in each region should be mentioned as part of a capacity-building action plan.

- Trainees viz. disaster managers, planners, decision-makers, an official of line departments, engineers, NGO and CBO representatives and locals participating in a training programme on landslide DRR require a precise site-specific overview of landslide hazard, causes, vulnerability, risk and required mitigation measures. This type of information can be provided to the stakeholders only through meso and micro level LHZ/LSZ maps. Scientists and social workers emphasize the need for user-friendly validated maps of landslide hazard, data inventory, models, etc. in the hands of disaster managers.
- There is no institutional framework for the collection and preservation of basic landslide data. Similarly, the inventory maps of landslides are being prepared by different agencies in a scale not generally usable on the ground. Therefore, capacity building of professionals in the line department of States/UT's will be carried out for the creation of uniform landslide catalogue and mapping.
- No dedicated project for the training of professionals such as Civil Engineers, Geologist, Geotechnical Engineers, Disaster Managers, etc. as trainers for mitigation and management of landslides to reduce risk in collaboration with other national and international agencies by involving new tools and methods. Formulation and implementation of mitigation projects are invariably left to be carried out by the State governments.
- Most of the training programs on landslides DRR have generalised contents dealing more with the concept, definitions and types of landslides, etc. Case studies indicating effective preparedness, mitigation, response, recovery and rehabilitation pertaining to a landslide event are missing in most of the training programmes.
- Fewer training programs are organised at village and ward level. Training programmes at the village level are not linked to any financial incentives and the villagers attend these programmes at the cost of their daily wages or farming hours.
- There are virtually no training on landslide safe site selection for construction of new houses. Remedial measures using the local slided material for instant temporary stability.
- There is a lack of initiative to combine the modern technical knowhow with the coping mechanism of local communities developed by them through experiential learning of generations.

- Educating local women as key stakeholders need to be promoted, as women and children tend to be victims of hazards, but can also be more effective change-makers in the community.
- Educating locals about the landslide dam formation and LLOF (landslide lake outburst flow) and its consequences downstream is another aspect that has not been given due importance so far.
- Lack of proper training, awareness and in many cases, ignorance, non-adherence to land use regulations have encouraged unplanned slope cutting and overloading for commercial gains. The recently enacted slope modification regulations of the Aizawl Municipal Corporation can be a good model for other regulatory bodies in landslide-prone areas to follow.
- Even though staff engineers are considered necessary in Municipalities, the position of a staff geologist, geo-morphologist is not present in the Line Department of States such as Municipalities. It is important to create staff positions in Municipalities; PWD's and districts administration with high landslide risks.

b. Suggestive Interventions

- Inclusion of new technology inputs for capacity building and training programs on landslide DRR
- Identification of genuine targets group for training on landslide DRR
- Upgradation and simplification of the contents of the training programme on landslide DRR
- Strengthening the response framework through capacity building and training of vulnerable communities at the grassroot level
- Elimination of communication gaps in reading the signs of landslides and for necessary pre-emptive action
- Provisions for financial incentives

V. Preparation of Mountain Zone Regulations and Policies

The sub-group strategy describes the formulation of land-use policies and techno legal regime, updating and enforcement of building regulations, review and revision of BIS code/guidelines for landslide management, proposed amendment in town and country planning legislation, regulations for land use zoning for natural hazard-prone areas as well as additional provisions in development control regulations for safety in natural hazard-prone areas, additional provisions in building regulations/bye-laws for structural safety in landslide hazard-prone areas.

There is no land use policy in the country at National, State and local level for implementation. The cities of the Himalayas are growing and beginning to turn into the mountains of garbage and plastic, untreated sewage, chronic water shortages, unplanned urban growth and even local air pollution because of vehicles. These towns need to be planned, particularly keeping in mind the rush of summer tourists. Many states have experimented from banning plastics to taxing tourists to better respond to these issues. But they need support and new thinking on everything on traditional architecture practices, local water management and different systems of sewage and garbage management.

a. Problem/gaps

- National Landslide Mitigation Policy (NLMP) which is a must for National Landslide Mitigation Strategy (NLMS) should be common all over the country while concerned State/UT specific landslide mitigation strategy must be developed by the State/UT and be area/problem specific but must reflect the NLMP.
- The existing bye-laws/regulations at the local body or state level should be incorporated in the NLMP and NLMS. They should not contradict each other.
- Best practices which are used to mitigate landslide at the local level and activities which can be held responsible for the landslide hazard should be documented.
- Since preventing/preparing for the landslides/slope instability is much easy and cost-effective than mitigating/reclaiming the landslide/slope instability. Emphasis must be given to prevention /preparedness in NLMP and NLMS.
- Unplanned developmental activities in mountains including huge investments in the construction of non-engineered roads in rural areas and lack of drainage which is exacerbating and increasing risk.
- The necessity of load-bearing tests, hazard zonation, slope and land-use maps to guide urban planners for clearing constructions.
- Impact of landslides on rural communities where the loss of large areas of farmland has ruined livelihoods and puts a big question mark on food security in the mountains. Compensation for land lost in landslides for farmers needs to be addressed.
- The necessity of DDMAs to apply for and utilise disaster mitigation funds.
- DDMA to obtain land-use, asset and other useful maps from West Bengal State Remote Sensing Centre.
- Need to focus on implementation and enforcement of laws/regulations and accountability.

- Need for better coordination between the Panchayats, Line departments, Forest department and Municipal authorities for management of jhoras and drainage outside municipal limits.
- State-specific landslide mitigation strategies to be formulated to address specific issues of each mountain state.
- Urban centres and towns in mountain areas being burdened beyond the carrying capacity by tourism and rural-to-urban migration. Need for satellite towns.
- The municipal bye-laws must provide for construction activity to be regulated in areas, which fall in hazard zones or areas close to rivers, springs and watersheds of the towns. In many cases, these provisions exist in the bye-laws but have not been strictly enforced.

b. Suggestive Interventions

- **Policy Level Intervention**
  - Government Orders issued by the various State Governments contain a number of provisions to be followed while sanctioning the building plans by the Development Authority, Special Area Development Authority, Corporation, Municipal Board and also by the concerned government department while selecting the site for construction the building. Due to the lack of technically qualified manpower either with the sanctioning authority implementation is very difficult and could not be followed. The State governments/Sanctioning authorities should have a panel of reputed and technical personnel including SDMA, who can assist as and when required to the building sanctioning authority.
  - Central government may consider giving suitable incentives for adopting landslide safe construction.
  - Necessary amendments in Section 26 of Special Area Development Authority Act 1986, as provided in Section 28 (k) of UP Planning and Development Act, 1973, regarding sealing of building, should be made.
  - It is observed that most of the government projects are outside the purview of sanctioning authority. Therefore all such projects when designed should take care of safety provisions and certified by the concerned architects/engineers.
  - At present, there are number of Acts/Rules/Regulations applicable in the states. There should be single legislation to control development and building activity which could be formed taking into consideration the present legislative framework and incorporating the suggestions made.

- Government and government agency buildings, which are designed by the Government technical department should follow strictly the provisions suggested for safety against natural hazards.
- Buildings constructed under the Pradhan Mantri Awas Yojana (PMAY) and other Government Schemes should strictly follow the provision of Indian Standards.

- **Technical Level Intervention**
  - As most of the government projects like hospital buildings, schools and others are of standard 'type' design, the provision of structural safety against natural hazards should be reflected in all such project in the drawings, and used/ implemented on the site.
  - Government departments like PWD/ Rural Engineering Services (RES) should incorporate in their curriculum related to the construction of buildings, the requirements of IS4326. The corresponding schedule of rates should also include the detail of additional features which are required to be done as per IS 4326.
- **Community Level Intervention**
  - Standard Building Plans, having provision of safety should be made available at the community level, which may consider standard house design of different types of plots, community halls and other common use buildings.
  - There is a need to bring awareness at all levels of society, first of all, a high-level awareness program for decision-makers regarding safety against natural hazards.
  - Awareness/training program is also required to be systematically arranged for engineers/officials working with local authorities regarding safe site selection, construction, bye-laws, regulations, quality control etc.
  - To further increase awareness at the Community level in rural areas, combined training of BDOs/ADOs at district level should be arranged. BDOs should be capacitated to further train people at the block level.

VI. Stabilization and Mitigation of Landslides and Creation of Special Purpose Vehicle (SPV) for Landslide Management

The sub-group strategy document emphasized on problems, gaps in Standard Operating Procedure (SoP), suitable methodology and mitigation of critical landslide. The sub-group strategy aims at providing necessary full techno-financial support to landslide-prone States, who would submit Detailed Project Reports (DPRs) to project sanctioning agency for taking up site-specific landslide mitigation measures. Landslides are site-specific in nature and since the vulnerability is different in different locations, the methodology/ technology for mitigation of each landslide will be different, involving different activities.

The design and construction part of the protective structures for landslide mitigation may be undertaken by the concerned Department of the particular State such as PWD and if required they can approach the technical expert institution for necessary technical advice. The present engineering practice relies on fragmentary approaches involving quick-fix treatments of landslides, which end up in their recurrence, year after year, at the very same locations. The paucity of funds, absence of delivery capacity, and urgency to deal with immediate landslide danger are generally cited as reasons for this continuing practice. The permanent solutions to our major landslide problems may appear at the face value to be capital intensive and even unaffordable, but in the true analysis, the benefits of permanently fixing landslides will far overweigh. Presently, geotechnical engineering practice is sufficiently advanced to blend the short and the long term recommendations in a design package by taking recourse to the well established observational method of design and construction. This method makes use of field observations and their analysis during the process of implementation to alter the design as the work proceeds. Therefore, it is necessary for the creation of Special Purpose Vehicle (SPV) and Centre for Landslide Research Studies and Management (CLRSM) to create a techno-scientific pool of expertise in the country. Necessary geotechnical/geological studies required to prepare the DPR may also be allowed to prepare by suitable and authorised technical concerned Department/consultant group of the State government.

a. Problem/gaps

- Scattered pool of expertise and peace meal project mode work by expert institutions.
- Strengthening education, research and training in landslide mitigation and management of professionals, State Officials and other stakeholders.
- Lack of pace-setting best practices of landslide treatment/mitigation.
- Updation of Science-Technology-Innovation based holistic, eco-friendly and sustainable approaches in addressing landslide mitigation and management.
- Non-coherence of landslide mitigation with the challenges posed by extreme weather events, natural resource management, urbanisation, industrialisation and constructions that unfortunately remain largely unregulated.
- Lack of mainstreaming of landslide mitigation with environmental protection and development planning.

b. **Suggestive Interventions**

- **Preparation of methodology/SOP for identification of most vulnerable landslide sites in States for mitigation purpose**
    - A National Task Force of expert/committee of professionals should be constituted to catalogue, study and decide management strategies for all the known problematic landslides in the country in consultation with the State governments, district administration and the civil society.
    - Appropriate agencies, institutions and teams should be identified, shortlisted and mandated to implement the programme in a phased manner.
    - Rational criteria to classify an individual landslide as minor, medium or major should be prescribed at the outset for uniform adoption and
    - Adequate funding should be provided through national landslide mitigation and management projects or by one-time funding from the Central government.
- **The suitable methodology for planning, engineering and control measures for the execution of landslide stabilisation work and tools/methods for monitoring, inspection, audit and timely lines for completion of the work.**
    - Site-specific landslide stabilisation and mitigation of problematic landslides and reconstruction-rehabilitation of the affected community by State government's.
        - Preparation of DPRs on the basis of NDMA Template by the States/ Agencies.
        - DPR's will be scrutinised by the Group of Experts on the basis of Cost-Benefit Analysis (CBA).
        - Monitoring, inspections & audit of mitigation work by Expert Group.
- **Need for Procedure for specialised training of professionals/personnel in landslide mitigation and management at the national level.**
    - There is an urgent need to devise procedure and well-defined mechanism to impart specialised training professional and personnel dealing with landslide mitigation and management. The proposed CLRSM will facilitate and create guidelines, procedure and will impart specialised training to enhance the functioning level of various professional, State government officials and other stakeholders.

Outcomes

The strategy document is a small but significant step towards mainstreaming and strengthening of landslide disaster risk reduction (DRR) in disaster management activities to reduce risk and minimise losses. The strategy document could provide guidance to the concerned States/UTs, Ministries/Departments and other stakeholders during conceptualisation/finalisation of their developmental projects. It will also serve as a guidance for the SDMAs/DDMAs in formulating their disaster risk management initiatives.

Conclusion

The need for formulation of a national and local level strategy for landslide risk reduction was felt. This strategy is also fulfilling the fifth target of Sendai Framework for Disaster Risk Reduction (2015-30) i.e., Substantially increase the number of countries with national and local disaster risk reduction strategies by 2020. Strategy document addresses all the components of landslide disaster risk reduction and management such as hazard mapping, monitoring and early warning system, awareness programmes, capacity building and training, regulations and policies, stabilisation and mitigation of landslide, etc. This strategy document envisages specific recommendations for the concerned nodal Agency, Ministries/Departments, States and other stakeholders, so as to avert or reduce the impact of future landslide calamities. For any further study on National Landslide Risk Management Strategy and reference a detailed version i.e., the strategy document and compendium may be referred.

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Long Term Landslide Mitigation Technique Illustrated- A Case Study

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Abstract

Landslide is the mass movement comprising of rock, debris or soil under gravity influence. The main slide triggering factors are rain and tectonic seismicity induced landslides occurring in the Himalayan belt of the Indian subcontinent. Anthropogenic activities like tunnel blasting for hydroelectric projects, unplanned excavations or cuttings of the side for road widening purpose activates failure mechanism. On the other hand, continuous blasting and tunnelling weaken the rock joint layers. Based severity of rock joints and rock surface conditions; rock structures have been characterised into different range of GSI chart. Thorough study and analysis are required to check the long term stability for these type of weak slopes with GSI range of 10 to 40 having fair, poor to very poor surface conditions lying close to important and sensitive structures. The present study reveals the effectiveness of preventive measure applied to the unstable slope stretch in the vicinity of Teesta stage III hydroelectric system. Finite element modelling has been carried out for the critical slide triggering stretch using Rocscience-Phase2 v8.005. Analysis has been carried out without and with stability measures. It has been observed that 50m vertical cladding wall having prestressed cable anchor with no base support survived the 2012 earthquake of 7 Richter magnitude scale with no signs of distress.

Keywords: Landslide; Himalayan belt; Long term stability; Finite element modelling; Prestressed cable anchor; Teesta stage III hydroelectric system

Introduction

Construction of dams in the seismic prone area is a challenging task. This requires proper geological and topographical analysis in order to evaluate structural behaviour

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and to obtain critical safety factors. Fig. 5.1 depicts factor causing the reduction in the shear strength in the same strata and adjoining layer. It can be seen clearly from this figure that how rain infiltrates through the persistent and non-persistent joints causing a decrease in shear properties and consequently creating detachment of block in blocky rock structure and slide in the highly jointed rock mass. The continuous build of pore water pressure generates a flow of muck or loose mass overlying the water-resisting strata.

The Teesta stage III hydro project is a huge mega-dam in Sikkim comprises of concrete face rock dam of 60 m height constructed across Teesta River near Chungtang village, which has seen multi-faceted impacts on the indigenous Lepcha people of Sikkim.

Fig. 5.1: Landslide mechanism induced due to Rainfall

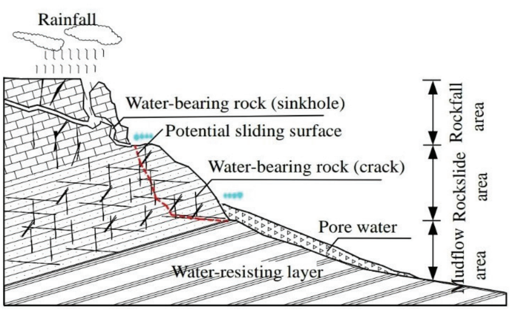


Fig. 5.2: Typical slided zone along road

Fig. 5.3: Map showing Teesta Stage III location

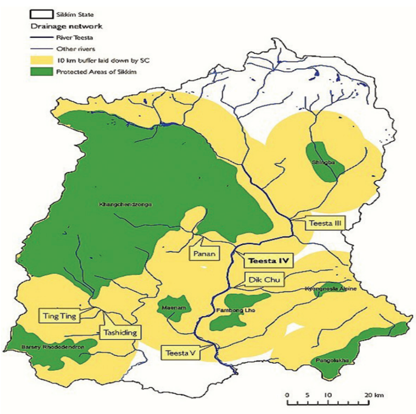


Fig. 5.4: Protection works for unstable portion

The unstable portion was observed during construction activities at the dam site and cutting of left abutment which was susceptible to failure. GSI of 25 shows the rock structure of disintegrated- poorly interlocked, heavily broken rock mass with a mixture of angular and rounded rock pieces. This value of GSI suggests a weak rock condition.

METHODOLOGY

Geological site description

Site geology of dam site area lies in the rock formation of central crystalline; subdivided into Chungthang series, Darjeeling gneiss & Rongli series of Pre-Cambrian age. Chungthang series comprises of quartz, biotite gneiss, biotite schist, calc-silicate and thinner bands of argentiferous – sillimanite heavily micaceous gneissose. Rock units are highly folded; asymmetric, isoclinal in nature with NE dips.

Landslide issue was observed due to excessive stripping and cutting of the left abutment as shown in Fig. 5.5. About 1 lac m^3 debris slide down the hill after the cutting work at the left abutment of the dam site.

Fig. 5.5: Site condition before the start of work

Fig. 5.6: Before commencement of cable anchoring

Geological Strength Index (GSI) of the slope is computed based on rock mass structure and surface condition of discontinuities with reference to GSI chart published by Hoek and Brown (1997). The extent of weathering, joint roughness and infilling material between the discontinuities, joint apertures were studied and analysis; based on which ratings were assigned to reach GSI value (Pandit et al., 2019). GSI value of 25 was observed showing rock structure of disintegrated- poorly interlocked, heavily broken rock mass with a mixture of angular and rounded rock pieces.

Calculating shear strength reduction factors

The finite element of slope requires selection of constitutive relation between stress-strain behaviour, which depends upon the material type. Equivalent continuum modelling with elastic and plastic ranges is adopted for these type of disintegrated rock layers.

In a present case study of FEM analysis, Generalised Hoek Brown (Hoek et al., 2002) with material constants “m_b, “s” and “a” have been reported and derived from GSI values (Equation 1-3) and verified from Rocscience roclab data software (Pandit et al., 2019). GHB material model adopted for the gneissose and surface weathered rock, while Mohr-Coulomb material model for overburden soil.

$$m_b = m_i \cdot \exp\left(\frac{GSI-100}{28-14D}\right) \tag{1}$$

$$s = \exp\left(\frac{GSI-100}{9-3D}\right) \tag{2}$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right) \tag{3}$$

The extent of the problem domain of left abutment of Teesta dam site has been modelled, discretized with fine mesh density. The slant height of slope is 226 m having an average inclination angle of 62^0. The average depth of overburden mass and top weathered surface rock is around 24 m, 12 m respectively. The slope has been modelled with boundary conditions having slope face as free, vertical sides as roller support allowing vertical displacement, the base is restrained from any moment (i.e.hinged support). Six noded triangular with uniform type mesh is adopted for the study as recommended in Rocscience manual (2012).

Fig.5.7: Schematic diagram of proposed cable anchor stabilization at left abutment of dam axis

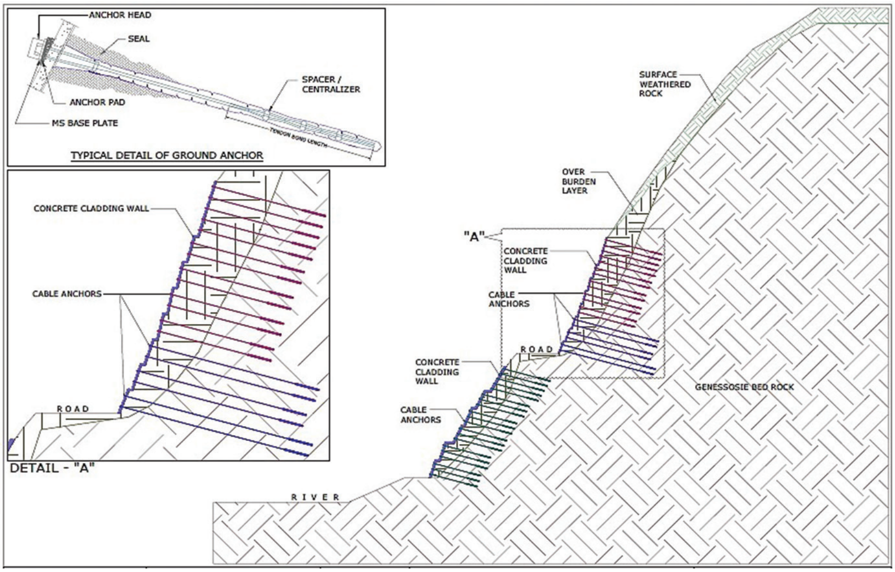
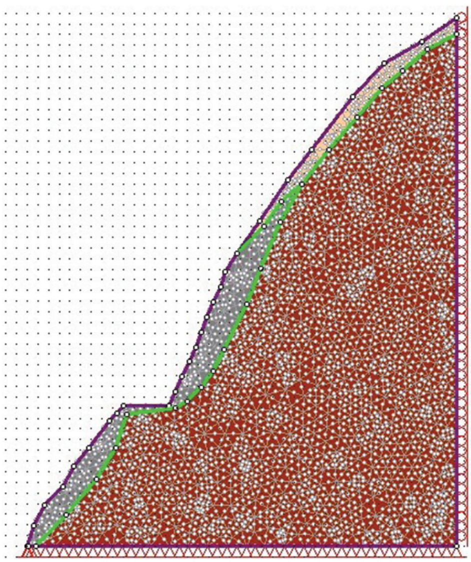
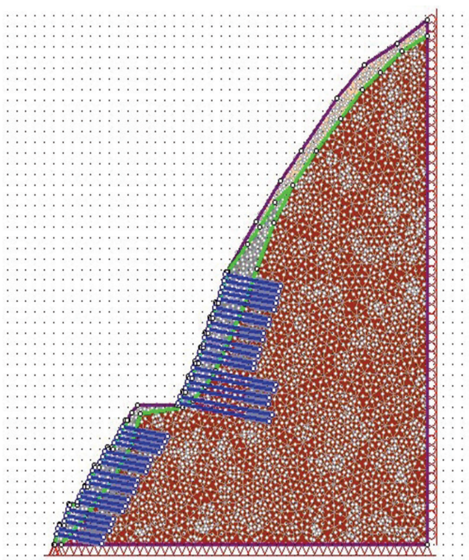


Fig. 5.8: Typical discretised mesh of slope Figure 5.9. Discretised mesh of slope with stabilisation





Once material properties are assigned and mesh discretization is done, the slope stability analysis has been performed for static and seismic analysis (Zone IV) having a coefficient of the horizontal seismic load as 0.15 and coefficient of the vertical seismic load as 0.1 acting vertically downwards and away from slope; which is the severe load combination. Pore water pressure with Ru as 0.25 has been considered for the analysis.

Table 5.1: Properties of Materials used in FEM Analysis

Material Type	Overburden	Surface weathered rock	Bed rock (Genessosie)
Material Model	Mohr Coulomb	Generalized Hoek Brown	Generalized Hoek Brown
Unit weight (kN/m^3)	21	22	24
Cohesion (kN/m^2)	98	215	482
Friction angle (degree)	28	17.88	19.79
mb	-	0.066	0.108
s	-	1.62e-06	3.73e-6
a	-	0.544	0.531
Intact UCS (Mpa)	-	70	120

Once all material properties and discretisation has been done for static and seismic condition, the slope is analysed to assess critical strength reduction factor. Slope models have been also analysed after applying the stabilisation measure in the form of prestressed cable anchor with RCC cladding wall. The cladding wall of 500 mm thickness is lifted in stages of 7 to 10 metres. Taking about the construction method, the slope protection using cable anchors with cladding wall is a top-down construction process, so there is minimal stress occurs at the toe of the slope. For the present case study, the toe protection is applied above and below the slope bench. As per IS 14448-1997, the fixed anchor length is designed based on the three factors such as failure of rock and grout bond, failure of grout/anchor bond and failure of the anchor. Based on these recommendations, failure criteria of rock and gout bond observed as critical with bond stress 160 kN/m and fixed anchor length as 12 m. Perforated drainage pipes are installed along the slope profile (cladding wall) to relieve the pore water pressure.

Table 5.2: Properties of Stabilised Material used for Protection System

Material Type	Prestressed cable anchor
Anchor type	Tie back member
Diameter (mm)	150
Ultimate tensile capacity (tonne)	100
Length (m)	25 to 40 m
Out plane spacing (m)	3
In plane spacing (m)	3
Bond stress (kN/m)	160
Pre tensioning force (tonne)	120

Results

Analysis of left abutment at dam axis shows that the slope is quite unstable under the static and seismic condition with SRF 0.95 and 0.81.

Fig. 5.10: Horizontal displacement (Left side) and Total displacement (Right side) for unstable slope under static condition

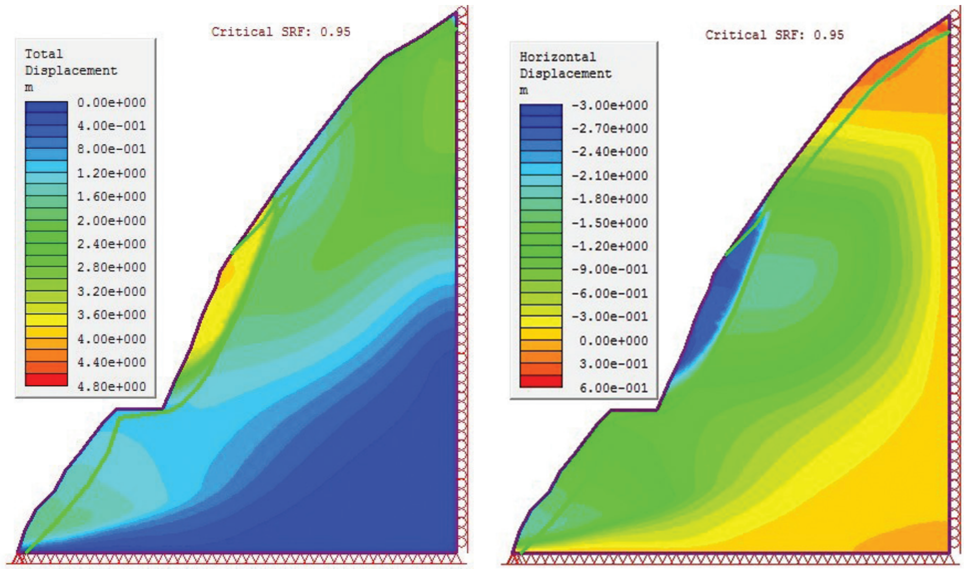
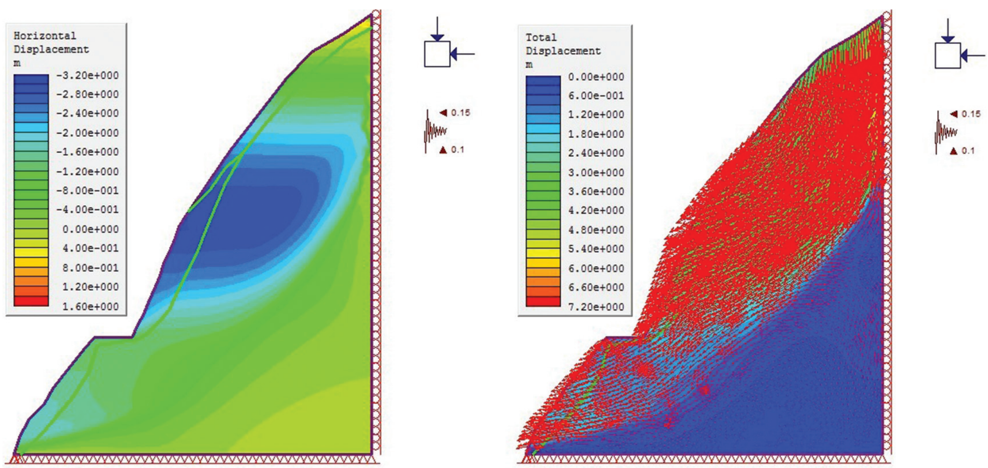


Fig. 5.11: Horizontal displacement (Left side) and Total displacement (Right side) for unstable slope under seismic condition



Following results depicts the effect of inclusion of prestressed cable anchors in reducing horizontal displacement, total displacement. Critical SRF value of 1.65 with 41 mm displacement for the static case (Figs. 5.10 to 5.14) and 1.32 critical SRF with 47 mm displacement has been observed under seismic case (Figs. 5.15 to 5.17).

Fig. 5.12: Horizontal displacement (Left side) and Total displacement (Right side) for stabilised slope under static condition

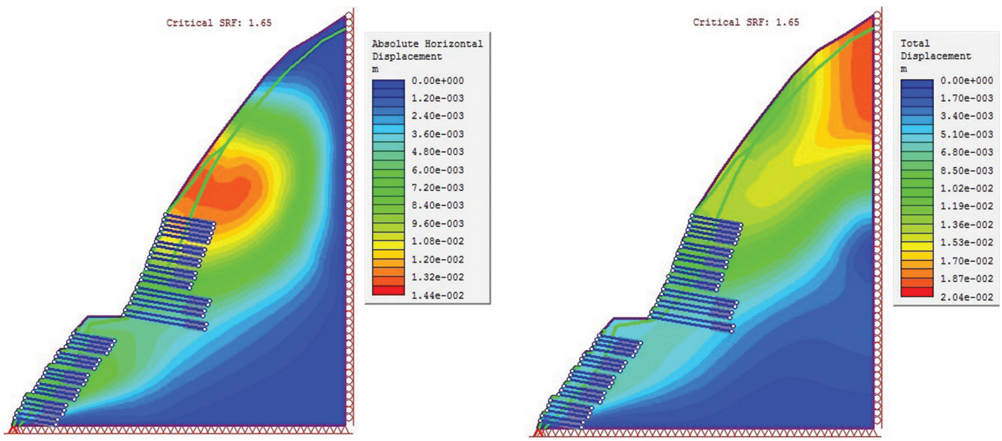


Fig. 5.13: Variation of strength reduction factor with maximum total displacement for static case (with stabilisation)

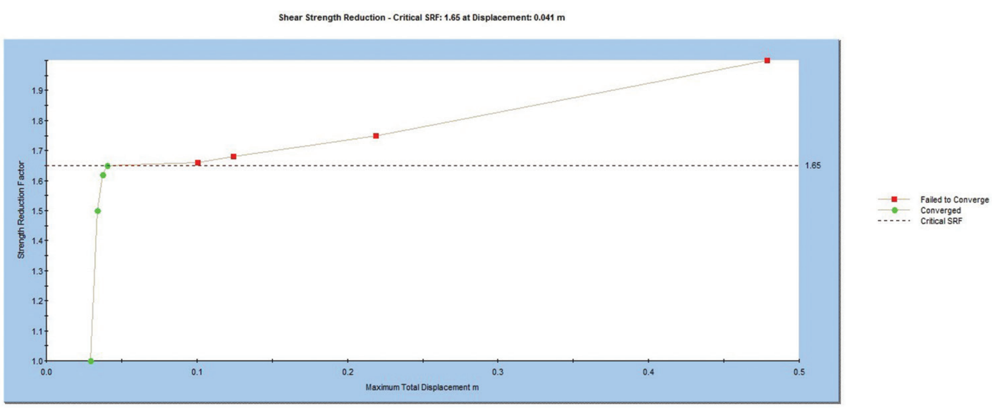


Fig. 5.14: Horizontal displacement (Left side) and Total displacement (Right side) for stabilised slope under seismic condition

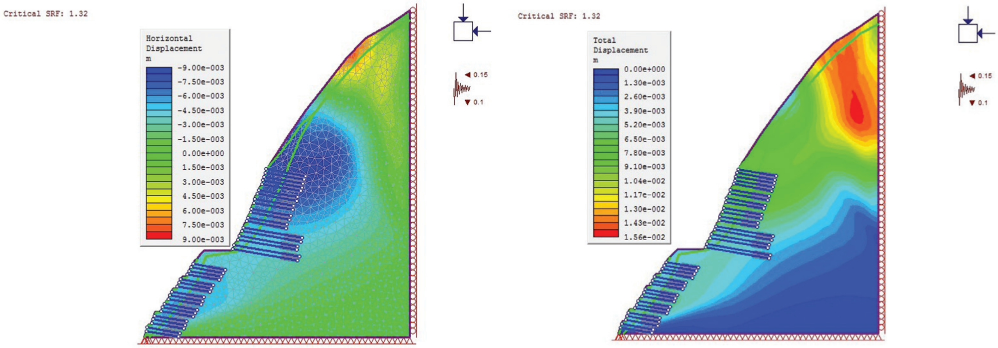


Fig. 5.15: Variation of strength reduction factor with maximum total displacement for seismic case (with stabilisation)

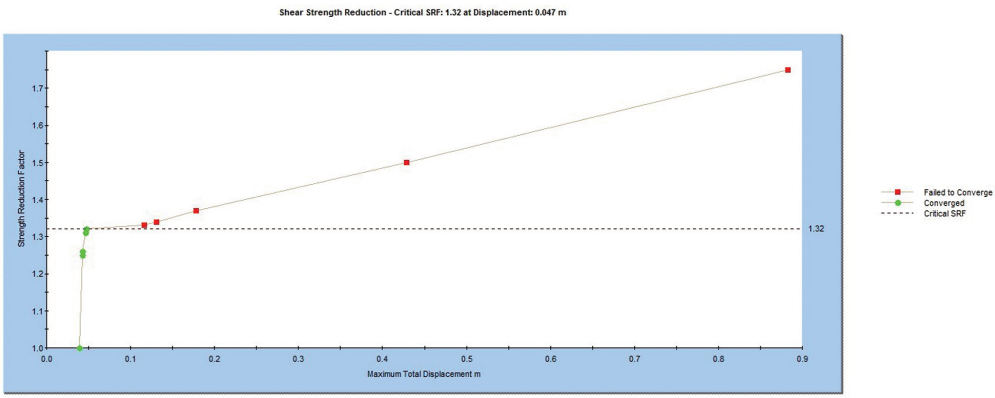
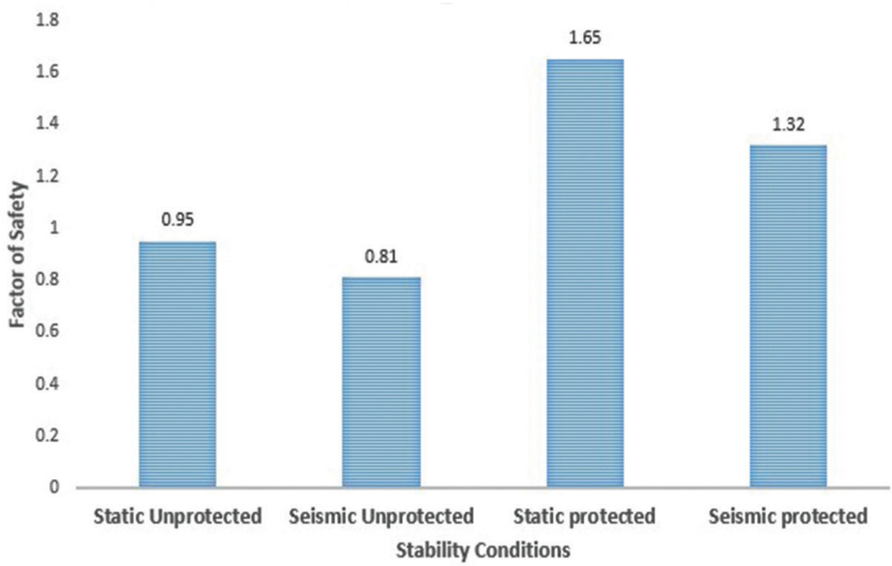


Table 5.3: Comparative Table between Protected and Unprotected Stability

Parameter	Static Case		Seismic Case	
	Unprotected	Protected	Unprotected	Protected
F.O.S	0.95	1.65	0.81	1.32
Max. Displacement (m)	2.6	0.041	2.8	0.047

Following chart shows the relative increase in critical SRF values for stabilised and unstabilised conditions under the static and seismic case.

Fig. 5.16: Variation of strength reduction factor under different stability conditions



Discussion

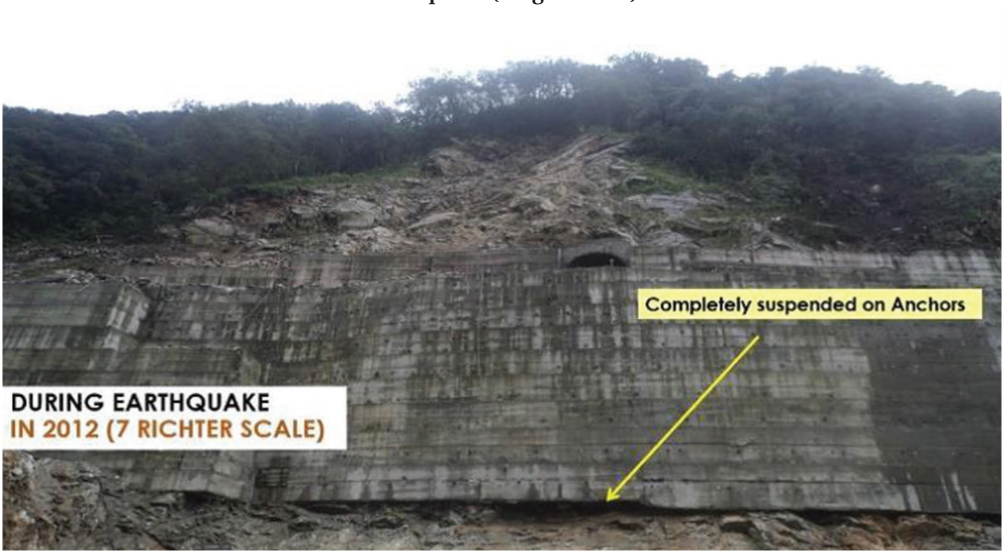
Stabilisation of poor class rock in seismic and region of high pore pressure is very vital. Use of prestressed cable anchor provides an effective and long term solution. It is clear from the above finite element analysis results that there is a significant improvement in the critical safety factor results. It has been observed that there is 73.68 per cent and 62.96 per cent improvement in safety factor values under static and seismic conditions respectively after inclusion of prestressed cable anchors. Displacement is also a critical criteria for slope stability. In the present case, displacements restrained within the nominal limits for the static case and seismic case.

The mechanism behind the stabilisation is due to increase in the shear strength along the failure surface, as pretension cable anchor increases the active resistance resulting from the stage of mobilisation of sheared mass along the slip line.

Conclusions

The present analysis shows that there is a significant improvement in the safety factor results. The current status of the project site is that the 50 m vertical cladding wall having prestressed cable anchor with no base support survived the 2012 earthquake of 7 Richter magnitude scale with no signs of distress.

Fig. 5.17: Condition of stabilised slope with prestressed cable anchor after 2012, earthquake (Magnitude 7)



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Landslide Risk Assessment for a Part of Coonoor Town, Tamil Nadu

Evangelin Ramani Sujatha*

Abstract

Landslides are off-late a frequent and common hazard in the hill and mountain terrains all over the world. The changing climate pattern with the increase in the number of extreme rainfall events has led to an increase in the frequency of landslides that disrupt the social and economic fabric of these hills and mountain regions. This scenario mandates a thorough analysis of the physical factors causing landslides in a particular geo-environment and the threshold of a triggering factor that initiates the landslide activity. This information can be used to map the spatial propensity of the landslides and the temporal probability of its occurrence which can be expressed as the spatial distribution of hazard in the selected region. A hazard zonation map is a vital tool that can be used to identify the exposure of the region to the hazard. Risk is interpreted by comparing the hazard map and the land use & land cover map. Risk zonation can be used to plan the developmental activities and strategies for mitigation. This is of interest when the region under study has an economy based on tourism. Risk assessment can help suggest alternate economies and optimize tourist infra-structure in a hazard resilient and sustainable fashion.

Keywords: Landslides, Climate Change, Hazard, Risk, Tourist Economy

Introduction

Landslides are geomorphic processes that cause not only considerable to damage to life and property of people in the affected region but also result in severe environmental degradation. Froude and Petley (2018) report that 75 per cent of the landslides reported worldwide between 2004 and 2016 occurred in Asia with India having a considerable share. Geological Survey of India (2016) also report that nearly 12.6 per cent of India's land area is susceptible to landslides, particularly the Himalayan arc and the Western Ghats region. This study attempts to assess the risk exposure of a part of Coonoor town in Nilgiris

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District, Tamil Nadu, falling in the Western Ghats region to landslides. Landslides are one of the most frequent hazards that plague Niligiri District, Tamil Nadu particularly during the north-east monsoon season when copious amounts of rainfall arebeing received. Analysis of physical factors causing landslides, identification of factors triggering landslides in the region and their respective threshold limit to understand the landslide occurrences in the selected area. Literature shows that a number of physical factors like lithology, degree of weathering, slope aspect, slope gradient, curvature, relative relief, soil type, soil thickness, drainage density, distance from drainage lines, proximity to roads and railways, etc. can cause landslides (Pardeshi et al., 2013; Sujatha and Rajamanickam, 2015; Teerarungsigul et al., 2015; Ciampalini et al., 2016; Sujatha 2017). The effect of each physical factor on aiding the occurrence of a landslide is a function of the local geo-environment. Landslide susceptibility map which describes the spatial distribution of the zones susceptible to landslides expresses the cumulative effect of the physical factors contributing to landslides. Several probabilistic, heuristic and deterministic models have been adopted by various authors (Alleotti and Choudhary, 1999; Keefer and Larsen, 2007) to map landslide susceptibility. This map describes only the spatial component of landslide analysis. The temporal aspect of landslide analysis is given by the landslide hazard map which is based on the return period of the threshold of the triggering factor (Jaiswal and van Westen, 2009). Landslides can be triggered by rainfall, seismic activity and anthropogenic activities though rainfall is observed to be the most common triggering factor. Assessing the impact of landslides on the social, economic and environmental components of the region through risk analysis is necessary for the effective town and hazard mitigation planning in the region. Susceptibility, hazard and risk map prepared for the selected area to suggest suitable strategies to minimise the impact of landslides in the region.

Study Area

A part of the Coonoor town (urban area) is selected for the study. It has a total area of 10.55 sq. km. The average temperature of the region is 17°C. The lowest temperatures recorded are in January and the highest in May. The normal rainfall is 1773 mm (Sujatha and Suribabu, 2017). Rainfall is spread throughout the year but maximum rainfall is received in the north-east monsoon season between October and December. The altitude varies between 1520 m and 2105 m above the mean sea level. The climate reflects the altitude of the region. Coonoor town is densely populated with high tourist influx all through the year. Tea cultivation and processing is the largest economic activity in the region followed by tourism.

Materials and Methods

The thematic maps were extracted from ASTER DEM of 30 m × 30 m resolution, Survey of India topographic maps and satellite images. Slope, aspect, curvature, relative relief, land use, type of soil, drainage density, topographic wetness index, proximity to roads and railway lines were used to estimate the susceptibility of the region. Frequency ratio method was used to model landslide susceptibility in the region. Rainfall was observed to the triggering factor in the region. Daily rainfall data and landslide occurrences between 2007 and 2018 were used to identify the threshold limit and estimate the probability of landslide occurrence using Poisson's probability model (Jaiswal and van Westen, 2009). The landslide hazard map was compared with the land use map to assess the risk.

Results and Discussion

Physical Factors Causing Landslides

Past landslide incidences were used to identify factors causing landslides in the region. The landslide dataset was divided into two parts, landslides that occurred before the year 2009 and landslides that occurred 2009 and after. The first dataset was used to build the frequency ratio model and the second dataset was used for validation of the model. Frequency ratio is a simple statistical model that expresses the ratio of the area that has been affected by landslides in a particular class to the ratio of the area of a class to total area. Table 6.1 presents the frequency ratio of the various classes in a thematic layer. Higher frequency ratio indicates the class in a particular theme is more relevant to cause landslide in the given geo-environment.

Table 6.1: Frequency Ratio (FR) of the Thematic Factors

Theme	Class	Frequency Ratio	Theme	Class	Frequency Ratio
Slope (°)	< 5	0.44	Soil Type	Sandy Loam	0
	5-15	1.09		Loamy Sand	1.27
	15-25	1.18		Sandy Clay	5.22
	25-35	0		Clay	0
	>35	0	**Drainage Density (km^2/km)**	Low	1.00
Relative Relief	Low	0.89		Moderate	1.43
	Moderate	1.41		High	0.46
	High	0		Very High	0

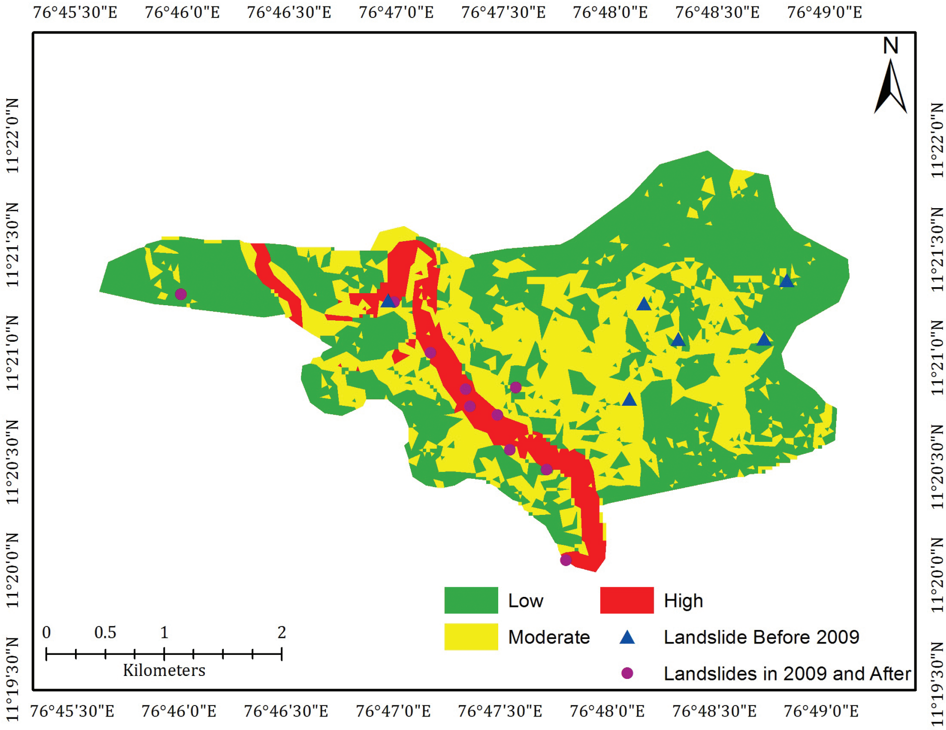
Aspect	Flat	0	**Topographic Wetness Index**	Very Low	0.84
	North	0.20		Low	1.00
	North East	1.39		Moderate	0.98
	East	2.50		High	1.36
	South East	0.62		Very High	0.57
	South West	0.97	**Distance from Railway Lines**	Railway Line	5.19
	West	0.53	**Distance from Roads**	National & State Highway	3.75
	North West	0.31		Major District Road	1.70
Curvature	Convex	1.01		Other District Road	0.05
	Flat	0.96		Village Road	0.76
	Concave	1.01			
Landuse	Forest Plantation	0.13			
	Built-up Land	1.36			
	Agriculture	0.95			
	Forest	0			

The frequency ratio analysis shows that all factors selected for the study are relevant in causing landslides except curvature where landslides are spread almost equally in all classes. It can be observed from Table 6.1 that slopes between 5°-25°, moderate relative relief, east-facing slopes, sandy clay soil, slopes with moderate drainage density and high topographic wetness index, proximity to railway lines and national & state highways are prone to landslides.

Landslide Susceptibility of the Study Area

The frequency ratio is applied as weights to each class in the thematic layers and are combined using ArcMap software. The resulting map gives the spatial distribution of zones susceptible to landslides in the selected area (Fig. 6.1). The railway line and the national highway falls in the high susceptible category. The built-up area also falls both the high and moderate susceptible category.

Fig. 6.1: Landslide Susceptibility Zones in the Study Area



The susceptible zones are classified into low, moderate and high categories and occupy an area 54.4 per cent, 36.9 per cent and 8.7 per cent respectively of the total area. Frequency ratio is calculated for each category with landslide incidences that occurred after 2009 (Table 6.2). The frequency ratio increases with the increase in susceptibility category indicating the good performance of the susceptibility map. Also, Table 6.2 shows that a higher number of landslides are present in the high susceptibility category which has the least area. This again indicates the good performance of the selected model (Can et al., 2005; Sujatha and Rajamanickam, 2015).

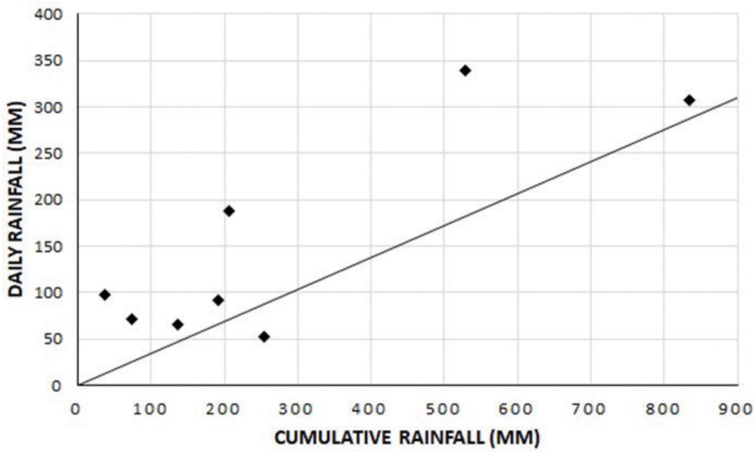
Table 6.2: Frequency Ratio of the Susceptibility Categories

Category	Area Pixels	Landslides Pixels	% Slides	% Area	Frequency Ratio
Low	6383	45	0.168	0.544	0.31
Moderate	4325	82	0.306	0.369	0.83
High	1020	141	0.526	0.087	6.05

Temporal Analysis and Landslide Hazard Zonation

Daily rainfall data and landslide records for the years between 2007 and 2018 were used to determine the rainfall threshold and return period of threshold rainfall. Both single and multiple landslide events were considered as a single event. Daily rainfall and three-day cumulative rainfall was studied to determine the rainfall threshold. Daily rainfall of 70.8 mm was estimated as the minimum rainfall required to initiate a landslide in the study area (Fig. 6.2). This minimum threshold corresponds to the occurrence of small and medium-sized landslides.

Fig. 6.2: Relationship between Daily Rainfall, Cumulative Rainfall and Landslides



Gumbel's distribution was used to determine the return period of threshold rainfall. The return period of threshold rainfall was 1.37 years. Major landslide events recorded in November 2009 showed that the daily rainfall required to initiate them was around 188 mm and a three-day cumulative rainfall of 206 mm and above was required to trigger landslides of huge volume. In the year 1979 and 1993 such extreme rainfall events caused multiple large landslide events in the study area and the daily rainfall recorded during these events were 177 mm and 310 mm, respectively. Based on these observations, it can be said that major landslides occur when a daily rainfall of more that 180 mm is experienced. Poisson's probability was used to determine the probability of occurrence of a landslide when the threshold is exceeded. Daily rainfall exceeded the threshold rainfall 45 times in the study period and 17 landslides occurred when the rainfall exceeded the threshold rainfall in the same period. The probability of a landslide occurring when the threshold is exceeded is nearly 36 percent.

Risk Analysis

Risk is the exposure to hazard and is a function of the damage potential (Anbalagan and Singh, 1996). Risk analysis can help in improving the resilience to risk of the area affected by landslides. A comparison of the landslide hazard zones with the land use map shows linear infra-structure like railway lines & highways and built-up area is most affected by landslides. Also, the damage potential is high for these categories. The number of landslides has increased over the period of investigated time. Anthropogenic activities have led to an increase in landslides. Increase in the density of the built-up area has increased the risk to landslides. Also, slope modification for regular maintenance along the railway lines and widening of roads have contributed to an increase in the number of landslides.

Conclusion

Landslides have emerged as a major natural hazard in the selected region in recent years. The changing climate regime with a number of extreme rainfall events warrants a thorough analysis of the physical and triggering factors causing landslides. Local thresholds are more contributive to the design of early warning systems and this study will be a step forward in this direction. Risk assessment can help combat the losses due to landslides and help in building a community more resilient to the risk of landslides. The economy of the region is largely based on tourism and related activities mandating a thorough risk assessment. The regions more prone to risk here are the slopes along the railway lines & major roads and the built-up areas. Slope protection works along the slopes like retaining walls and breast-walls have provided. Hence, turfing the slopes with plants like vetiver grass and asparagus can help improve the stability of the slopes. Also, regular maintenance of the drainage outlets can help in slope protection.

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Landslide Challenges Due to Widening of Road Section Between Udhampur and Chenani Along National Highway-44, Jammu and Kashmir, India

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Abstract

Widening of 295 km National Highway-44 in Jammu and Kashmir is an important developmental project. The highway passes through Outer Himalayan and Higher Himalayan sequences of rocks and is frequently affected by landslides at various places. The paper deals with 22 km Udhampur-Chenani section of the highway within the Siwalik sedimentary sequence. The area is prone to landslides on account of fragile geological, topographic and hydrological conditions. The study area has high rainfall intensity and numerous old landslides zones. At the project feasibility stage, project authority has identified the landslide-prone area and suggested precautionary measures but during the construction work, various unpredicted landslide and ground sinking events happened which given trouble in road construction cost and project completion time. In this paper, the challenges faced due to landslide and ground failure as failure of old slide adjutant to road construction, agriculture and residential ground failure at a higher altitude due to road construction, the collapse of high tension towers in cut slopes; its impact on construction activities and project completion time; are discussed with mitigation measures for unidentified landslide related challenges.

Keywords: Landslide, Geological and hydrological factors, Colluvium deposits, Mitigation measures

Introduction

Jammu and Kashmir (J&K) is northern most state of India and 90 per cent of geographical area falling under Himalayan range. J&K state is very important in view of political, defence, tourism and spiritual purpose. Jammu to Srinagar National Highway-44 (NH-

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44; earlier NH-1A) is only one connecting road to Kashmir valley and Leh-Ladakh region. Jammu-Srinagar national highway NH-44 is lifeline for everyone. This road is passing through Outer Himalaya to Higher Himalayan range with very complex and landslide prone area. NH-44 is frequently closed during the rainy season, which cut off the Kashmir valley to remaining India. For smooth connectivity, road widening work is under progress.

Study area, Udhampur- Chenani road section(road chainage Ch 67.00 km to 89.00 km from South to North) is part of Jammu- Srinagar National Highway -44 which is 22 km long and widening work was awarded to GECPL in the year 2015 (Fig. 8.1).

Topographically area has highly variation; road elevation varies from 327 mean sea level (msl) to 2400 msl (Jammu to Patnitop). Road blockage due to landslide and snowfall is normal event along the highway. Climatically, the area belongs to temperate to subtropical region. Selected road section received rainfall twice in year i.e. 40-50 mm per month from January to March, and very heavy rainfall occurs between July and September, reaching up to 650 mm of rain. The annual rainfall in the temperate region varies from 600-900 mm with snowfall. River Tawi is Major River flowing along this section of road.

The Geomorphology of the road section is characterised by moderate to steep valleys. Presence of narrow river valley and numerous small perpendicular tributaries, mild to steep hill slopes and colluvium deposits at the toe of the slopes, are the main geomorphologic features of the project area. The slopes on both sides of river valley are varying generally from 30° to 70°. The geomorphology of the area seems highly erosion-prone due to presence of weathered rock mass on the slopes, loose rock blocks, old landslide debris and rock slide debris deposits all along the slopes. The major valleys being longitudinal and are aligned in WNW-ESE direction.

Geologically, study area belongs to Outer Himalayan range, consisting of Murree formation which is overlying the buried surface of the northern fringe of the Indian shield. Lithologically, these sediments constitute semi-consolidated to consolidated sandstones, siltstone, mudstone, shales, conglomerates and clay beds. Structurally these rocks display broad anticlines and synclines. A series of thrust is a characteristic tectonic feature in the nearby study area. The most prominent among them are Main Boundary Fault (MBF) from the Outer Himalayan strata.

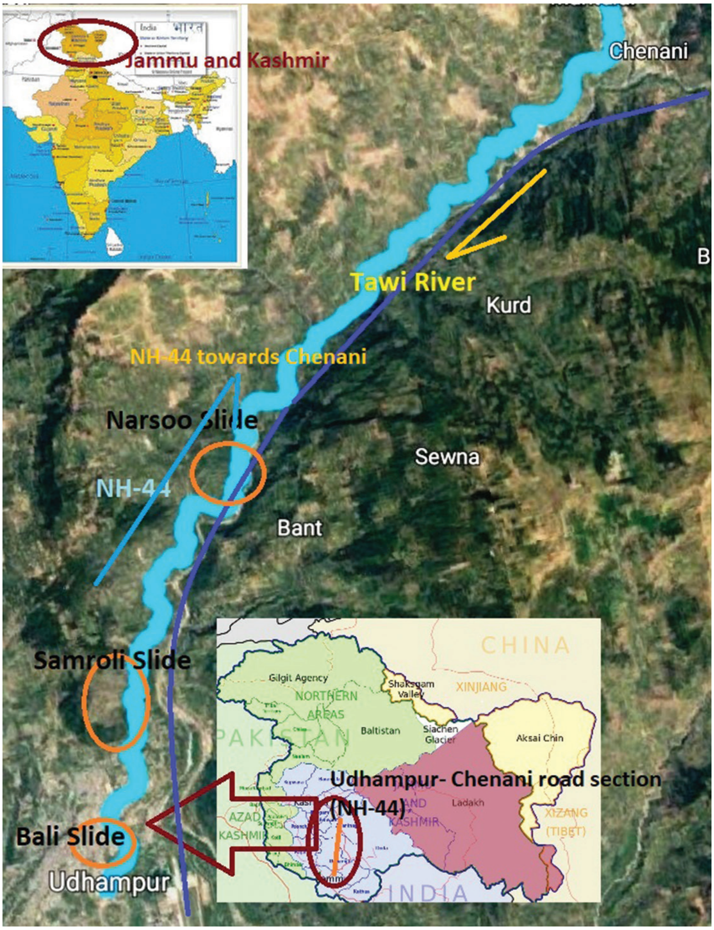
The Outer Himalayan rock mass is highly disturbed having a general dip of approximately 30° at the higher levels and 70° at the lower levels on either side in folded strata with NNW-SSE strike. There are three major sets of joints: bedding joints, cross joints and micro joints dipping 20° to 80°. Steeply dipping joints predominate over gently dipping joints. However, change in the strike and dip direction observed at localise place that is due to the folded nature of the rock. Earthquake history, microseismicity and the presence of longitudinal and transverse thrust faults in the region, it is concluded that the study area is quite vulnerable to earthquakes. The Jammu and Kashmir partial comes under Seismic Zone IV and partial in zone V.

As per approved design and provided ROW (Right to Work), GECPL had started the hill excavation but due to poor geology; faced various slope and ground failure which disturbed the unidentified problems such as collapse and cracks in residential building, agriculture land, high tension electricity tower and usually identified landslide. GECPL had faced losses in form of manpower, machineries, precious project time and project cost. Challenges due to unidentified landslide/ground failure issue have been discussed in this paper with probable causes and mitigation measures, which will beneficial in other projects also and government bodies should take care in an upcoming project for saving the project time and project cost burden on civil contractor.

Landslide Zones and Probable Causes

A landslide along the NH-44 is normal phenomena. Several old landslide zones have observed along the existing highway. Landslide is the result of a wide variety of processes, a combination of one or more factors which include geological, geomorphological, geotechnical, hydro-meteorological factors such as rainfall and snow; and the reduction of shear parameter due to an increase of pore water pressure by saturation during spells of torrential precipitation and undercutting/toe erosion by water bodies. Rockfalls occur along closely spaced and steeply dipping joints, while planar and wedge failures occur due to the intersection of adversely-oriented joint planes. Slides on the thick colluvium deposits have also observed. Colluvium deposit had made up of cobbles, boulders and Silty sand and clay-sand soil which increase the chances of liquefaction in presence of water. Main landslide areas are Bali landslide, Samroli landslide and Narsoo landslide which were observed by various researchers such as Bhat et al. (2002); Chingkhei et al. (2013); Pandey (2018); Singh (2006), slope stability report (2016); Verma (1966).

Map 1: Location Map of study area with major landslide zones along NH-44 (Udhampur -Chenani Section), J&K



Causes of landslides in the studied area are divided into three factors, discussed below

- Geological and topographical factors: Geologically area is made up of weak rocks with four to six sets of joints and covered with overburden materials consist of boulders and soil. Slope angle (45° to 70°), alternate bands of weak rocks and valley side natural slope have increases the frequency of landslide.
- Hydrological factors: As the area is made up of loose overburden material with weak rock and unfavourable joint orientation, nominal rainfall causes the erosion/sludge flow and as rainfall varies 600-900 mm annually with twice in a year; water percolated in between the joints and causes liquefaction, which is one of the causes of a landslide

in this area. Frequency of Cloud burst event in higher ridges is increasing and causes the flash flood and brings boulders and sludge and blocks the road.

- Human and construction activities: For fulfil the daily basis needs, the local public had made the agriculture land after cutting the natural vegetation as well as diverted the water for irrigation and drinking purpose through small drains. During diversion of water, water percolated underneath the soil which causes the slope failure in some area. Excavation along the road or in loose strata, disturbed the natural slope and sinking or sliding of the area observed in some locations.

Discussions

During the Detailed project investigation (DPR) stage, old landslide zones have been identified and provided the protection work such as Breast wall, Retaining wall, Concrete Cladding and others. Minor soil failures were taking care but some slide zone was activated due to natural slope failure, geological and hydrological factors. In the Udhampur- Chenani road section, various slope/ground failure issues have been faced during construction activities which were not identified earlier. Due to the sudden ground and slope failure, happened in the form of activated old landslide zone, damages of houses, agriculture and forest land, high tension tower collapse or in critical condition. Due to these unpredicted sudden ground failures events adversely impacted the project. Mainly three patterns of failures are observed:

- Failure of active old slides adjutant to road construction
- Agriculture and residential ground failure due to road construction at higher altitude
- Collapse of High tension towers above the cut slopes

I. Failure of active old slides adjutant to road construction

Ch. 68 + 900 km to Ch. 69 + 300 km, Ch. 75 + 600 km to Ch. 76 + 400 km and Ch. 84 + 500 km to Ch. 84 + 700 km are covered with thick colluvium material.Geologically synclinal structure Mudstone, Claystone and Siltstone are evidently. At the above locations, namely Bali, Samroli and Chenani, landslides respectively have occurred in recent past.

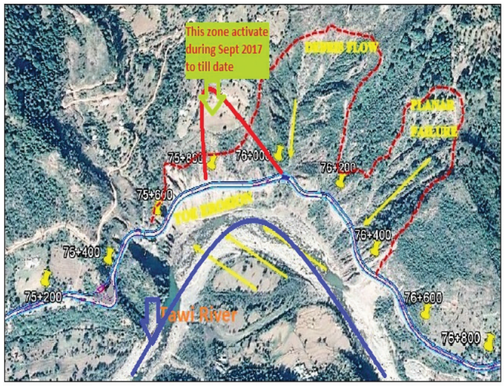
These areas show the wedge and planner failures due to an increase of pore water pressure and sometimes undercutting/toe erosion by rivers/water bodies which are activated during the rainy season.

The road widening work is started in the year 2015. River Tawi is flowing parallel to this road section. The area having 40°-50° topographical slope and various small water bodies. Following landslide failures have been faced by GECPL:

- Bali Landslide zone: Bali landslide zone is made up of colluvium material with 12-18 per cent water content, 25-41 per cent liquid limit, 17-20 per cent plastic limit, having Slity sand (SM) in nature. These sliding activated during the monsoon, due to liquefaction. In this section minor bridge was proposed to avoid the landslide disturbance. GECPL has permanently deputed the machineries for 3-4 months during monsoon season. Google earth image (Map 2) shows steep topography and colluvium materials in this landslide zone.

Map 2: Google Earth Image of Bali Slide

Map 3: Google Earth Image of Samroli Slide



- Samroli Landslide zone: This slide is in between Ch. 75 + 600 km and Ch. 76 + 400, differential and aggressive erosion of the Mudstone/shale layer in between the Sandstone layers. Soil properties are the same as the Bali landslide zone. Anticline and Syncline geological feature are well developed in between the Sandstones and Mudstone layer. The crested part of this syncline is dislocated along right limb by a dip-slip fault and along left limb by a tear fault. The Sandstone bands are fractured and blocky in nature and due to the joint orientation, a series of triangular troughs of erosion have been created in the weaker rock. During the rainy season the strata is water charged and lubricated along the joint planes and wedge failure and toe erosion beneath the Sandstone band; shown Samroli slide (Map 3).

  The bridge abutment in this location was constructed in the month of August 2017 but in the same year in the month of September, sliding started and completely blocked the NH -44 for one week. The bridge was also covered with sliding mass, about 200 m long and 70-80m high. More cracks were observed about 60-70 m away from the top of the slide area (Photo 1). The cracks width was 20-30 cm, 50-60 m long and depth up to 4-5 m and beyond (Photos 2 and 3). Cracks were developed in two high tension electricity tower foundation and agriculture land at the top of the landslide. Minor bridge abutment was cracked and settled due to this slide, which completely blocked the NH-44 for single lane also (Photo 4). The Cracks were filled with Kanker, Sand, Cementaggregate. Drainage was also provided to avoid the surface water percolation inside the cracks.

- Chenani Landslide Zone: Chenani landslide zone has colluvium material with 12-18 per cent water content, 25-41 per cent liquid limit, 17-20 per cent plastic limit, having Slity sand (SM) in nature above the rock. This area is about 150 m wide along with the existing road level. It is largely a combination of slump and flow of surface material. The slide material is composed of mainly rock fragments in a matrix of brownish-grey Silty sand. The maximum thickness of the colluvium is more than 10-20 m. The existing road had been affected by the slide several times. This slide was activated during the monsoon, due to abrupt floods.

Photo 1: Samroli Landslide with dimension and cracks marked, during Sept 2017 event.

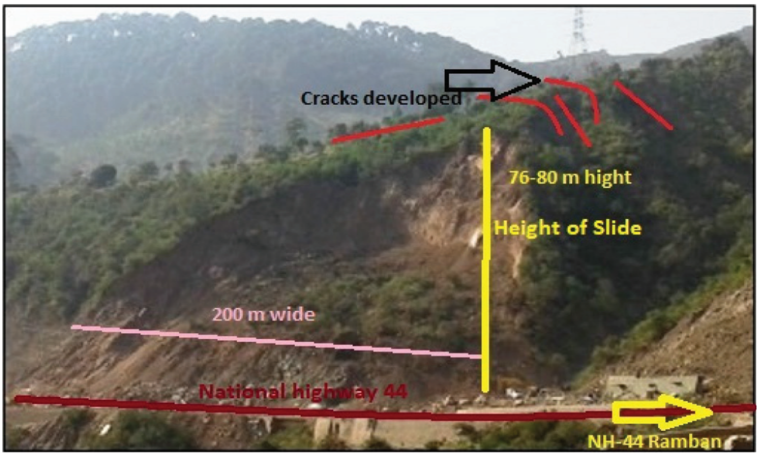


Photo 2 and 3: Cracks developed at top of Samroli Slide during September 2017 event.

Photo 4: Settlement of bridge and Cracks in bridge abutment A2.

II. Agriculture and residential ground failure due to road construction at higher altitude

Along the hill top, the houses and agriculture land were developed. Due to thick cover of colluvium and debris material as well as poor strength rock and toe erosion, several areas near the slide zone, grounds started sinking at Bali village (Ch 70 km to Ch 73 km), Toldi village (near Ch 78 km) and Narsoo village (Ch 81 km to 82 km), were affected:

- Bali Village: Maximum numbers of houses damage were reported in this area. Geologically the area is made up of thick colluvium materials- Silty soil with big boulders, slope are gentle with the medium cover of vegetation. Google Earth image is showing that areas forming spoon shape (Landslide prone area) due to hydrological and man-made activities in this area. Rock present at a deep level and slope angle are also high. Geomorphological, hydrological and geologically area have landslide favorable zone and old landslide zone. Presence of water, good agricultural soil had attracted humans for settlement in this area. Strength of colluvium materials would be very less and due to water percolation in subsurface lubrication form at contact plane of rock and colluvium, the landslide has been started at a huge level as shown in Photos 5-7.
- Toldi Village: Only one number of house damage was reported in this area. House is very near the ROW of the project. Geologically the area is made of thin colluvium materials 3-4 m before the Siltstone interbedded with sandstone rock, dipping gentle towards valley side, refer Photo 8.
- Narsoo Village: Three number of house damage complains were reported in this area. Houses are about 150 m far from the ROW provided to GECPL. Geologically the area is made of thick colluvium materials (3-4 m) and Siltstone interbedded with sandstone rock, dipping gentle towards valley side. Rock present at shallow depth and slope angle is high with valley side and increasing the probability of landslide refer in Photos 9-10.

Photo 5: Geological strata from Ch 70 + 600 km to 71 + 200 km, Bali Village

Photo 6: Geological strata from Ch 70 + 600 km to 71 + 200 km, Bali Village

Photo 7: Geological strata from Ch 73 + 400 km to 73 + 600 km, Bali Village

Photo 8: Geological strata at Ch 78 + 500 km, Toldi Village

Photo 9: Geological strata at Ch 81 km, Narsoo village

Photo 10: Geological strata at Ch 82 km, Narsoo Village

III. Collapse of High tension towers above the cut slopes

High tension electricity tower at Ch 71 + 300 km passing near the ROW were suddenly collapsed in the afternoon (60 m away from ROW) due to ground sinking at Bali slide zone. Study based on geological strata and slope failure prediction and importance of issues identified 28 numbers of towers in critical condition in which 26 numbers were suggested to be protected by micro piles, rock anchors and cladding wall as per site condition and 2 towers suggested shifting. Another tower (32.70 m from ROW) at same chainage was also collapsed within one month of collapsing of the first tower. Some tower photographs are given below (Photos 11-16):

Photo 11: High Tension Tower Ch 68 + 041 km

Photo 12: High Tension Tower Ch 69 + 115 km

Photo 13: High Tension Tower Ch 83 + 020 km

Photo 14: High Tension Tower Ch 84 + 797 km

Photo 15: High Tension Tower Ch 87 + 505 km

Photo 16: High Tension Tower Ch 87 + 886 km

Mitigation Measures for Landslide Zones

Precautionary measures for landslide zones, situated along the NH-44, are different due to various causes. Based on the pattern of failure in the studied area, selected for mitigation measures, mitigate the landslide due to road excavation needs excavation in flat angle, stepwise excavation, construct the supporting structures (retaining/breast/cladding wall as required) and for old landslide zone such as Bali, Samroli and Chenani area proper slope protection measures such as rock net, anchoring, shotcrete, rockfall barrier, Bio-engineering methods with a drainage hole for avoiding the pore water pressure are applied.

It is proposed to have the safety of agriculture and residential ground to be taken care on high priority and measure through geotechnical instrumentation (crack meter, settlement markers, deep settlement markers, etc.) and protection of toe would be the high priority through slope protection structures.

For the protection of High tension tower nearby the ROW land, retaining wall with a drainage hole and for tower having considerable distance from project boundary and protected through micro pilling and rock anchor.

Apart from above-discussed mitigation measures; three stages of landslide mitigation measures need to be adopted during the planning stage to the operation stage of the project.

1. **Project feasibility stage mitigation plan:** During the study of the project feasibility stage, following points needs to be taking care:
   - Old landslide and probable landslide zones to be identified properly and avoid such zones for construction activities. If not feasible to avoid, natural slope

protection measures to be suggested as well as recommend a bridge, tunnel as per site feasibility.

- A separate report needs to be prepared on geological, geomorphological, geotechnical, hydrological factors to be studied properly for impact on construction activity on landslide or natural slope throughout the project section.
- It is essential and mandatory that the landslide zonation mapping work of project affecting areas to be conveyed to local public and administrative body for avoiding such area for urbanization and physically mark such area. No financial funding or other facilities to be provided, if construction activities are done in that demarcated area.
- ROW for the project to be fixed as per the slope protection required land by authorities. Less land acquisition is cheaper during the initial stage of the project but challenges faced during the construction and operational stage of the project become much higher.

2. **During construction activities:**

- Stabilized the slope by preparing the benches with retaining wall after the removal the loose colluvium materials and Bio-engineering methods to be adopted.
- Giving proper drainage for avoiding ground failure. Catch water drain, drainage hole/ weep holes and diversion of water to be properly designed for a free flow of pore water.
- All the site representatives must know the slope hazard zone and suggested mitigation/precaution measures.
- Project approving agency must issue slope protection work as separate head to avoid incumbent financial and time load to the construction contractor for smooth tackle the slope protection work.
- As much as possible, avoid hazard-prone zone for disturbing the natural slope and if disturbing is essential then excavation to be done with all precautionary measures.
- ROW if not adequate and slope heights are more, the mitigation measures are to be judiciously provided.

3. **During the operation stage:**

    - All slope protection works to be done.
    - Instrumentation to be fixed at critical zones for daily monitoring of ground stability and issue warning at appropriate stages.
    - Inputs from public awareness are always beneficial to identify the upcoming ground failure.

Conclusion

Based on the types of landslides and related impacts in Udhampur-Chenani road section, it is concluded that area is covered with thick debris materials with a steep slope (angle = >60^0) and water bodies (rainfall, nallas and rivers). Natural features such as geology of area, geomorphology of steep disturbed slope and hydrological factors of subsurface water percolation are predominantly present in the area of study. The combined effect of these natural features mainly causes a landslide and related challenges during excavation.

Landslide study during the project feasibility stage is highly recommended with mitigation measures as per modern engineering solutions. Stepwise slope protection measures, protection from Wedge and planner failure and drainage are appropriate for safety aspect from landslide hazard. Funds also be allotted in infrastructure project for slope protection measures, that would save the project completion time as well as project cost escalation.

The mitigation measures need for Himalayan projects for smooth construction and long term performance. The impact of hill cutting and filling needs to approximate protection measures to be recommended as per modern engineering solutions.

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Kinematic Analysis of Rainfall Induced Rock Slide Along Roadcut Slopes – A Case Study on Dhalli Landslide, Himalayan Region

C. Prakasam,* Aravinth. R,* Varinder S Kanwar* and B. Nagarajan**

Abstract

The Himalayas is one of the highly prone regions for landslide disasters in the world. State and National Highways along the Himalayan region are unstable and are 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 research focuses on studying Kinematic analysis of Rainfall induced Rockslide and its slope stability along NH-22 near Dhalli Tunnel in Shimla town. Dhalli landslide which occurred in September 2017 is a structurally controlled landslide that occurred along a Road cut slope without proper toe support. Initial Studies about the orientation of the landslide is conducted through Kinematic analysis. 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. The final output reveals that the slope is partially stable with an SMR rating of 45. Slope stability analysis has been performed through SWEDGE model using the results derived from the field investigation. 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 the required value. A suitable Economically viable measure has been proposed like a Reinforced Wire Mesh Shotcrete as Slope Stabilization measure with a FOS value of 1.45 providing stability and support to negate the future occurrences of the slope failure.

Keywords: Dhalli Landslide, Slope Stability, Kinematic Analysis, Rainfall Threshold, SWEDGE.

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Introduction

"Landslides are simply defined as the downslope movement of rock, debris and or earth material under the influence of gravity. The sudden movement of materials causes extensive damages to lives, properties and local economy, etc." Sharpe (1938); Varnes (1978); Cruden (1991). Natural hazards happen due to variety of complex factors that are completely out of human control, where some disasters may have had human interventions. Some hazards are more prevalent and life-threatening such as floods, drought, windstorm, earthquakes, flash floods and cloud burst, etc. Landslide ranks 7th largest disaster and contributes to higher mortality rate (Alimohammadlou, Najafi and Yalcin, 2013). Landslide occurs due to various natural and anthropogenic factors. These causes include cloudburst, thunderstorms, Antecedent rainfall, and anthropogenic activities (Geological Survey of India, 2001). Landslides are mostly restricted to hilly terrains due to their rugged topography, steep slopes, soil content etc. Among other Geohazard landslide is found to be the fast-spreading epidemic due to various morphodynamic process and improper interaction of human beings with nature (Martha et al., 2013). On a global scale landslide is one of the major disasters worldwide that contribute a higher rate of causalities and economical losses. According to the report submitted by "International Association of Engineering Geology (IAEG)" on worldwide landslide events (1971 to 1975) to the UNESCO they have reported that landslide accounts for about 14 per cent causalities from natural hazards (Froude and Petley, 2018). In a report given by the International Disaster Database (EM-DAT) the landslide event occurred between 1990 and 2015covers about 4.9 per cent of the all the disasters that occurred in Asia (Guha-Sapir et al., 2018). In India, about 0.42 million sq. km are of landslide-prone areas. These areas include the North Western and North Eastern Himalayas and the Western & Eastern Ghats (Geological Survey of India website). While Nature being one of the dominant factors for active landslide anthropogenic activities have sped up the process in himachal Pradesh due to unplanned urban construction, deforestation, increasing in housing boards, hydro power projects, etc. (Chandrasekaran et al., 2013; Iverson, 2000). These factors not only threaten the damage and interpretation of transportation and other economic factors but also threaten human lives. Among other factors, Earthquake and Rainfall precipitation are being the two dominant factors that, while rainfall is the most significant in the initiation of mass movement of landslides (K. Sarkar, Singh and Verma, 2012; Singh, Verma and Sarkar, 2010).

The Himalayas being one of the youngest mountains on the earth surface undergoes complex slope movements due to tectonic and erosional activities leading to geomorphic denudation (Ashutosh and Panthee, 2016; Avcar, Ulusay and Mutlutürk, 2015). Landslides of various types Shallow, Deep, Complex, Pose severe hazards in the Himalayan region, where climate is the ultimate control in the process of initiation of landslides. Some of the worst disasters in the world have been caused by landslides (Pham et al., 2017; S. Sarkar, Roy and Raha, 2016). Most of the landslide in Himachal Pradesh occurs during monsoon seasons and very few occur during the winter seasons suggest that the landslides are initiate by extensive rainfall coupled with dynamic nature of Himalayan terrain. Due to such reasons the mechanism and induced parameters behind rainfall-induced landslide is being studied extensively all round the world and especially in the Himalayan region. Such studies have been able to quantify few relationships between rainfall precipitation and local landslide characteristics parameters.

Fig. 9.1: A section of Road has been washed away due to heavy downpour inBalichowki area, Mandi District (August 2019) source: Indiatoday, Landslide Along NH-21 (Chandigarh – Manali), December 2015. source: Indiatoday

Intensity and Duration of the rainfall are two controlling factors of the rainfall-induced landslides (Bhambri et al., 2015; H. Rahardjo, T.T. Lim and M.F. Chang 1995).

Prolonged rainfall on a soil surface generally, leads to deep-seated landslide failure while short outburst of intense rainfall leads to shallow failure. Shallow failure of landslides occurs due to the reduced Soil or Debri Shear Strength thereby shear strength reduction. Moreover prolonged or rainfall causes increased positive pore water pressure that further reduces the stability material along the slopes and ultimately prone to failure (Crosta and Frattini 2008). (K,undu et al., 2017) stated that one of the important aspects to consider is the ground vibrations caused due to the passing of heavy vehicles along the road cur slopes which have not been addressed much in any studies. Increased ground vibrations due to the movement of light and heavy vehicles on landslide mass can be 0.5 times stronger than gravitational vibrations which lead to increased shear stress and gradually reducing the Factor of Safety (FOS) of the material (Singh, Verma and Sarkar, 2010; Singh et al., 2016; K. Sarkar, Singh and Verma, 2012).

Himachal Pradesh situated along the Himalayan region is very prone to hazards like landslides throughout the year, especially during the monsoon season. They pose a considerable threat to local settlements, transportation corridor and human lives. The National Highway 05 (NH – 05) is an important transportation corridor that connects upper reaches of Kinnaur, Lahul and Spiti, Kullu districts to the rest of India. Rampur – Jhakri area located in Rampur Tehsil of Shimla district along NH-05 is one of the hotspots for shallow Debri landslide due to its thick deposits of soil materials. Seasonal rainfall coupled with road cut slopes for highway maintenance causes recurrent Debri and soil failure along this area leading blockage of roads and loss of communication for a long period of time. Many research worldwide has previously addressed the problems of landslide specific to geologic and geotechnical investigations (Hungr et al., 2001; Luigi and Guzzetti, 2016; Karabulut, Durgun and Durmus, 2004; Alimohammadlou, Najafi and Yalcin, 2013). Notable authors in India to work with various aspects of landslide, especially at local level landslide studies, are (Anbalagan and Parida 2,013; Anbalagan and Singh, 1996; Ansari, Ahmad and Singh, 2014; Bali, Bhattacharya and Singh, 2009; Bhattacharya et al., 2013; Ganapathy and Hada, 2012; D. P. Kanungo et al., 2006).

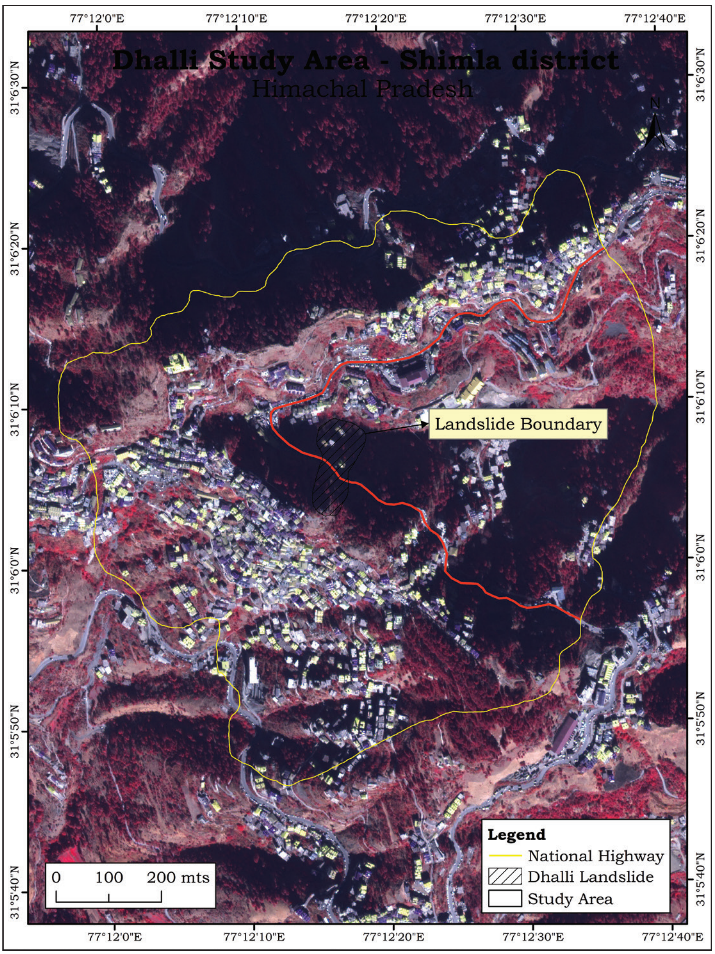
Need for Research

In the current research, an effort has been made to study the various causative factors of a recurring Rock failure along the Dhalli area based. Additionally, rainfall threshold investigation has been conducted for seasonal monthly and annual rainfalls to study the relation between landslide initiation and rainfall variations. Post failure slope stability assessment has carried out to estimate the critical FOS of the slide area and finally, stabilisation measures have been suggested to prevent the reactivation of landslide in near future.

Study Area

The Rock Slided area is located along the Dhalli Tunnel in Shimla town. The study area extends between 310546 and 310624 latitude and 771155 to 771240 longitude with a total geographical area of 0.85 Sq. km. The total height of the landslide from crown to runout distance extends for about 76.7 mts and the width of the landslide extends for about 18.6 mts. Due to the Rockslide nearby Settlements along the downhill and few parked vehicles have been damaged. Soil is mostly Sandy loam in nature and geology is mostly composed of Black Pyrite, Phyllite and Slate which are moderately strong according to GSI. The average rainfall of the area is about 999 mm with most of them occurring during rainfall season.

Fig. 9.2: Study Area



Data Used and Methods

The base map of the study area is digitised from "Survey of India" Toposheets 53E/04 at 1: 50,000 scale. Soil samples and other required information will be acquired through detailed Geological and geotechnical investigation of the landslide sites and also results retrieved from lab tests.

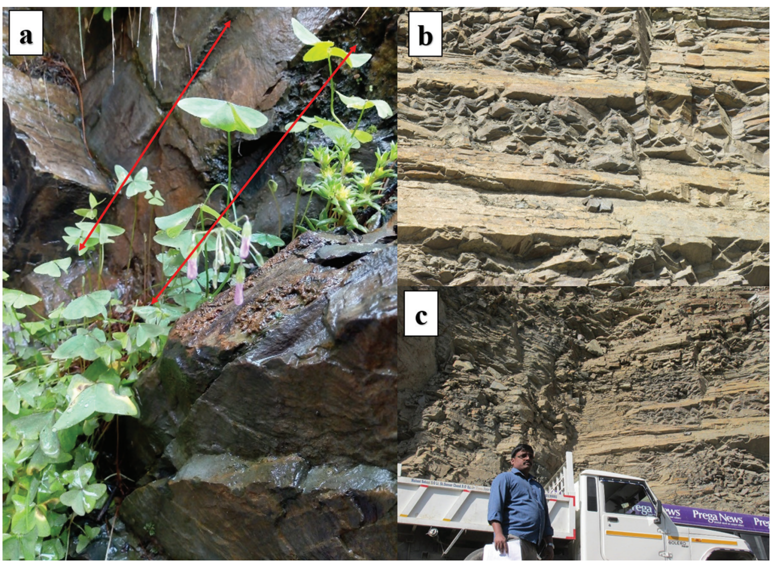
Table 1: Data used for the Research

Sl. No	Data	Source	Year	Resolution
1	Toposheets	Survey of India	1974	1:50,000
2	Large scale mapping	Worldview 2	2017	0.4mts
3	Geo-technical information	Field survey and lab analysis	2017 - 2019	-

Results and Discussion

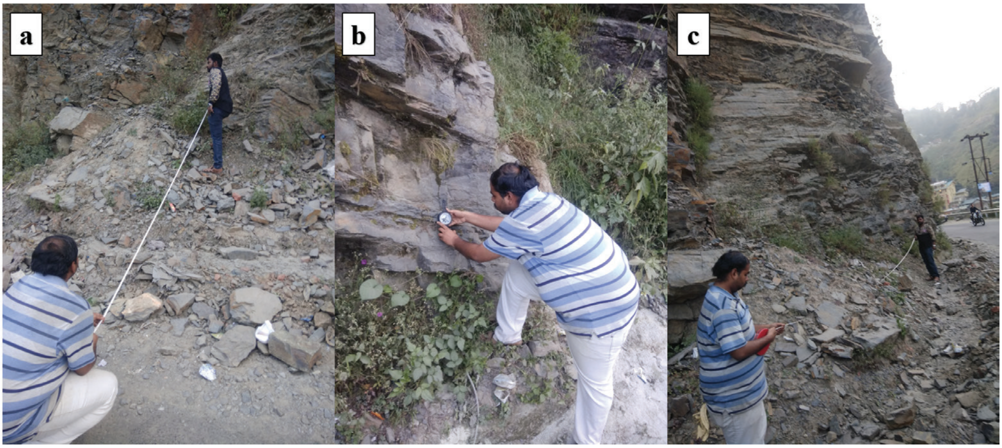
The Geological field investigation was conducted in the landslide area. The kinematic analysis was performed to analyse the type of rock failure in the study area. Kinematic analysis emphasis the use of Intersection of various joints and rock surfaces to estimate their potential weak zones and mode of failure. The mode of failure occurred in the study area is a wedge failure when two Joint sets plunge in the same direction as Slope face with plunge angle less than the slope angle.

Fig. 9.3: (a) Exposed Joint sets along the Surface the landslide; (b) Bedding plane and exposed joint surface along the study area; (c) Filed Investigation collecting various results on Geotechnical Parameters



Based on the data collected stereonet analysis was performed to determine the mode of failure for Dhalli landslide. Stereonet uses Circular graphs to represent the orientation of the Joint faces in terms of Dip direction and Dip amount.

Fig. 9.4: Collection of various joint sets from Study Area



The joint set J0 runs parallel to the bedding plane. Four different types of joint intersections were found as shown in the (Fig. 9.5).

Table 9.2: Various Joint sets

Sl.no	Joints	Dip Amount	Dip Direction
1	J0	33°	230°
2	J1	68°	2°
3	J2	71°	127°
4	J3	77°	80°
5	Slope face	81°	116°

Fig. 9.5: Stereonet with all Joint planes plotted

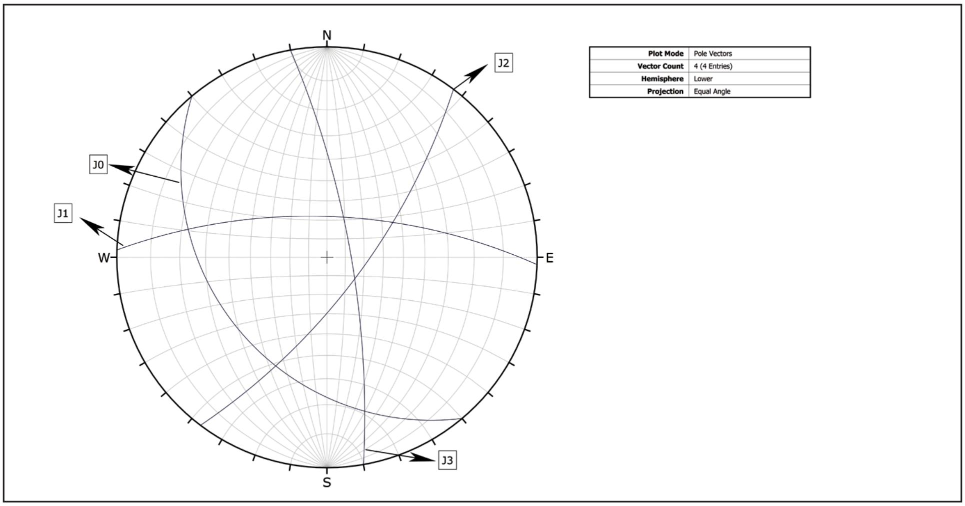


Fig. 9.6: Kinematic analysis of Dhalli landslide indicating Wedge failure

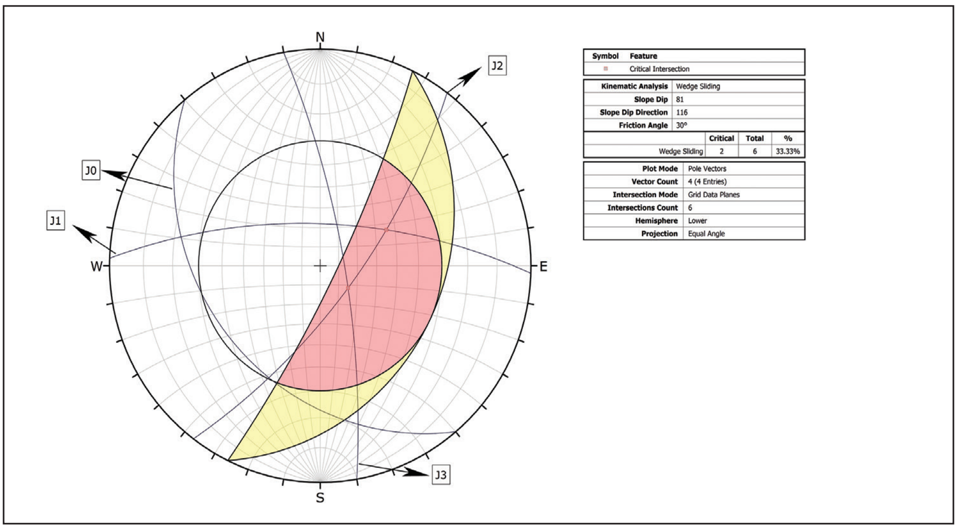
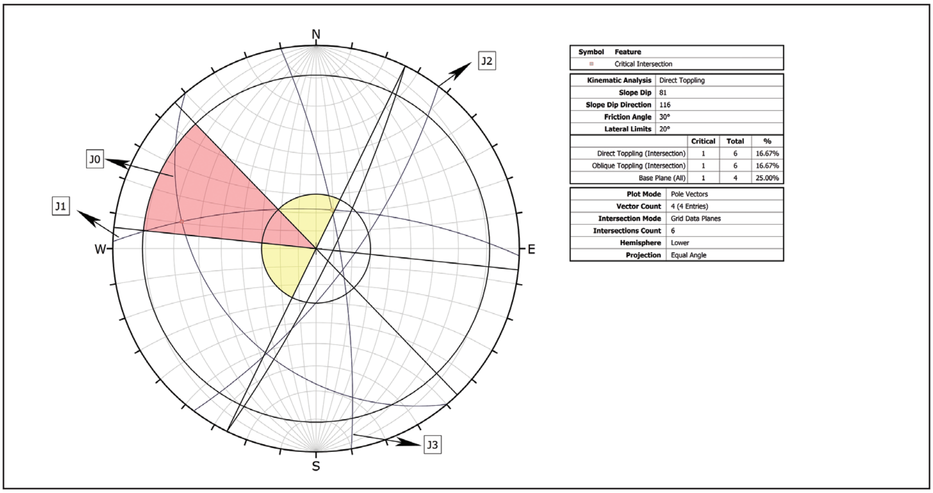


Fig. 9.7: Kinematic analysis of Dhalli landslide indicating Direct Toppling failure



Two lines J1 and J2 forming intersection line dipping away from the slope indicating it is wedge failure (Fig. 9.14). In (Fig. 9.14) the area indicated by pink colour represents the wedge failure conditions and unstable region for wedge failure. Point A represents the intersection of J1 and J2 and lies in a more unstable region, compared to the intersection of J2 and J3 (Fig. 9.15).

Rock Slope stability assessment and stabilisation measures for Dhalli landslide

Dhalli landslide which occurred in September 2017 is a structurally controlled landslide that occurred along a Road cut slope without proper toe support. Various joint sets running through the rocks made it prone for Shallow translational Wedge failure. Based on the data collected from field and lab analysis the slope stability of the landslide is computed using SWEDGE model through various computer simulations (Fig. 9.4a). The joint sets are plotted using a deterministic analysis of Mohr-Columb failure criterion. "The Mohr-Coulomb (MC) failure criterion is a set of linear equations in principal stress space describing the conditions for which an isotropic material will fail, with any effect from the intermediate principal stress being neglected". The Equation is represented as

$$\tau f = C_t + \sigma' n \tan\emptyset$$

Where τf = Shear strength of Intact rock
C_t = Cohesion of the Rock material
$\emptyset$ = Internal friction of the angle

Fig. 9.8: 3D view of the Dhalli Rock slope

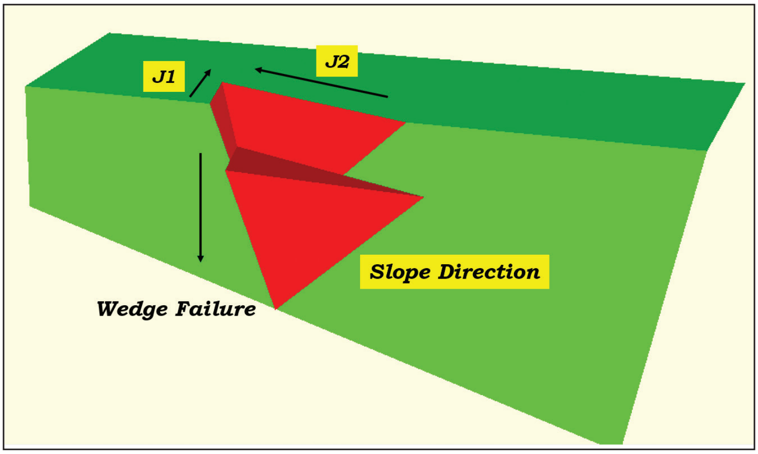
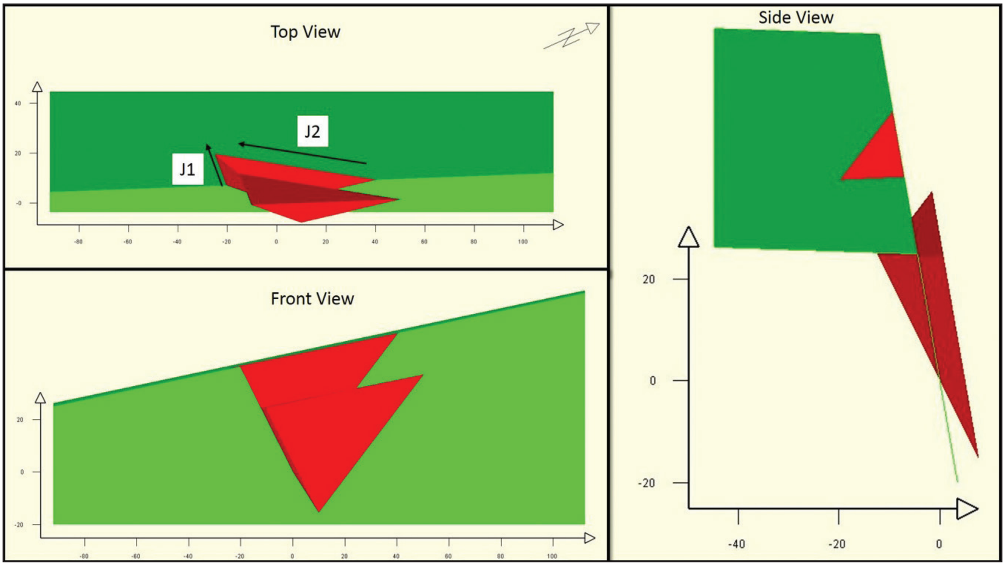
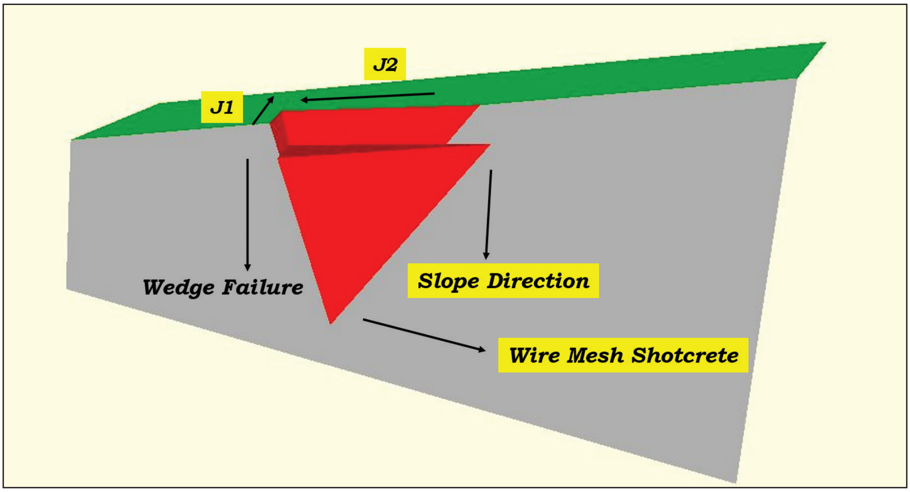


Fig. 9.9: Top, Front and Side view of the Dhalli Rockslide



Based on 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.

Fig. 9.10: Grey part indicating reinforced wire mesh with Shotcrete



Conclusion

Three different research methodologies were adopted to investigate the Geological, Geotechnical and Slope stability assessment and stabilisation measures of the study area. Site-specific Geological and Geo-technical investigation is carried out for specific landslides within the study area. The final assessment of landslide study involves estimating the stability of slopes and proposing suitable stabilisation measures. These studies are conducted through detailed geotechnical investigation of the landslides. Dhalli landslide which occurred in September 2017 is a structurally controlled landslide that occurred along a Road cut slope without proper toe support. Both field and lab studies were conducted to assess the stability of the slopes and provide suitable stabilisation measures. A geological field investigation was conducted at the landslide area. The kinematic analysis was performed to analyse the type of rock failure in the study area. Based on the data collected stereonet analysis was performed to determine the mode of failure for Dhalli landslide. Four different types of joint intersections were found as shown in the (Fig. 9.3a). Two lines J1 and J2 forming intersection line dipping away from the slope indicating it is wedge failure (Fig. 9.6b). In (Fig. 9.6b) the area indicated by pink colour represents the wedge failure conditions and unstable region for wedge failure. Point A represents the intersection of J1 and J2 and lies in a more unstable region, compared to the intersection of J2 and J3 Based on the data collected from field and lab analysis the slope stability of the landslide is computed using SWEDGE model through various computer simulations (Fig. 9.4a).

The joint sets are plotted using a deterministic analysis of Mohr-Columb failure criterion. Based on 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. Based on the nature of slope we applied reinforced wire mesh with Shotcrete type of stabilisation measure.

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National Interventions for Landslides Risk Reduction and Resilience

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Abstract

The safety of slopes and management of landslides have always been a major concern especially in the hilly regions across the globe. The landslide disaster engulfs precious lives besides devastating impacts on environment, infrastructures and structures. Moreover, the physiological blow by these catastrophic phenomenons is enormous and healing can take a long period. To regain the status quo of the affected area after the incidence of landslides have not always been a straightforward chore. In addition to the inherent characteristics of the slope, climate change and anthropogenic activities have augmented the frequency, intensity, risks and adverse impacts of the landslides. Therefore, safeguarding the fragile slopes required a holistic multi-hazard approach. India has always shown its commitment towards creating a disaster resilient nation. To achieve its goals, a number of interventions have been taken by the Government of India. Disaster Management Act 2005 was the first milestone that shifted the course of relief centric disaster management approach in the country to the holistic approach of preparedness, mitigation and prevention.

Taking the cognizance of the challenges posed by the landslides, major interventions and initiatives were carried out. The Disaster Management Act of 2005 provided the platform for these interventions and initiatives. The paper will illustrate national interventions taken for landslides risk reduction and resilience.

Keywords: Landslides, National Interventions, Resilience

Introduction

The stability of slopes has always been under the menace from the landslides, one of the major hydro-geological hazards which affects a large part of India from the mighty Himalayan range in the north to the coastal areas of the south. North and North-east states residing in the lap of the Himalayan ranges are highly landslides vulnerable

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regions in the country. As per an estimated around 30 per cent of the World's landslides took place in the territory of Himalayan ranges (NDMP, 2019). Apart from the Himalayan range, the other landslides prone areas in the country are situated in Western Ghats, Nilgiris and the Eastern Ghats.

Landslides not only pose threat to lives and environment but also adversely influence the livelihood, normal activities and psychology of affected community beside huge economic losses by the devastation of infrastructures and structures. It is always a big challenge for the community to return to the status quo after the episode of any catastrophic landslides.

Being situated on tectonically active plates along with unripe geology, brittle ecology, meandering rivers and climatic discrepancy the nation has faced unprecedented challenges from the landslides. Besides the own characteristics of the slopes, earthquakes and unprecedented rainfall also trigger the landslides, therefore, high landslides vulnerable areas in the country concurred areas with high seismic activities and high rainfall. Other disasters such as floods, flash floods, cloudburst, Glacial Lake Outburst Floods (GLOF) and Landslides Dammed Lake Outburst Floods (LLOF) are also capable of producing landslides. Further, the changing climatic variables have augmented the number of incidences of landslides in susceptible slope. Apart from the natural factors, the cruelty of humankind on the natural slopes to satisfy their insatiable ravenous for development without considering the measures for landslides risk reduction and resilience have created havoc for themselves as well as for the ecosystem.

The cognizance of the challenges posed by landslides for lives, economy and development laid down a number of interventions in the country. Prior, the site-specific quick-fix approach of debris removal and dumping was carried out at the solution for the landslides but with the enactment of Disaster Management Act 2005 and subsequent interventions more holistic approaches for prevention, mitigation and preparedness was adopted.

Global Interventions

To promote the landslide research and capacity enhancement for the benefits of humanity and the environment, an international non-governmental and n1on-profit scientific organization, International Consortium on Landslides (ICL) was created at the Kyoto Symposium in January 2002 (Sassa et al 2017). The objectives of crafting the organisation at international level were to protect the natural ecosystem, enhance the capacity of community, synchronization of international proficiency in landslides risk reduction and resilience and fostering global multidisciplinary programme on landslides.

Tokyo Action Plan of 2006 ushered to the establishment of International Programme on Landslides (IPL) that incorporates triannual World Landslide Forum (WLF) and the World Centres of Excellence on Landslide Risk Reduction (WCoE).

During the Third World Conference on Disaster Risk Reduction (3^{rd} WCDRR), 2015 in Sendai, Japan, ICL proposed the ISDR-ICL Sendai Partnerships 2015-2025 for global promotion of understanding and reducing landslide disaster risk. This confederation was adopted and signed by 17 United Nations, international and national stakeholders.

The Kyoto Landslide Commitment 2020 was endorsed subsequent of 2017 Ljubljana Declaration on Landslide Risk Reduction. The Commitment endeavoured to provide a framework for landslides risk reduction and resilience at all levels aiming to hasten and encourage the efforts for reducing the risk of landslides. It also fosters synchronising the key stakeholders concerned with the landslides and allied sectors (tools, information, platforms, technical expertise) for landslides risk reduction and resilience at the global scale (Kyoto, 2020 Commitment).

National Interventions

High Power Committee, 1999

Every coin has two faces likewise; disasters besides causing challenges to the humankind also provide equal opportunity to learn from them. Focusing on to clutch the learning of past disasters in India and outside the country, the High Power Committee constituted in 1999 endeavoured to provide a new conceptual framework to diminish the impacts of the disasters. The committee exhorted focusing on the preparedness for the prevention and reduction in addition to mitigation of the disasters (HPC, 2001). The natural as well as man-made disasters were classified under five categories. Landslides were placed under the "Geological Related Disaster" group. The committee highlighted that landslides are predictable and the adverse impacts posed by them can be minimised or even averted with proper and systematic studies. Priorities were given to landslide hazard identification, improved mapping, assessment to identify the existing/potential slope failures, land use patterns, control measures and development of reliable risk assessment beside sensitising the community about the threats of landslides and the possible solutions to minimise them it, they are unavoidable. They also emphasised to encourage the R&D on prediction and forecasting of landslides, especially for old landslides that have potential for reactivation, recurring landslides, and those occurring in the areas known to be hazardous.

Disaster Management Act, 2005

The Disaster Management Act, 2005 was the major intervention in the history of the country for effective disaster management. The DM Act virtually revolutionized the entire approach towards disaster management in India from a relief centric to holistic and integrated with an emphasis on prevention, mitigation and preparedness. The Act adopted many recommendations of the High Power Committee and formulated an institutional framework from the Central to the local levels through unified response mechanism and bestowing extensive powers on the Central Government and other disaster management agencies. It also ushered to develop a National Policy on Disaster Management and National Disaster Management Plan for creating disaster-resilient India.

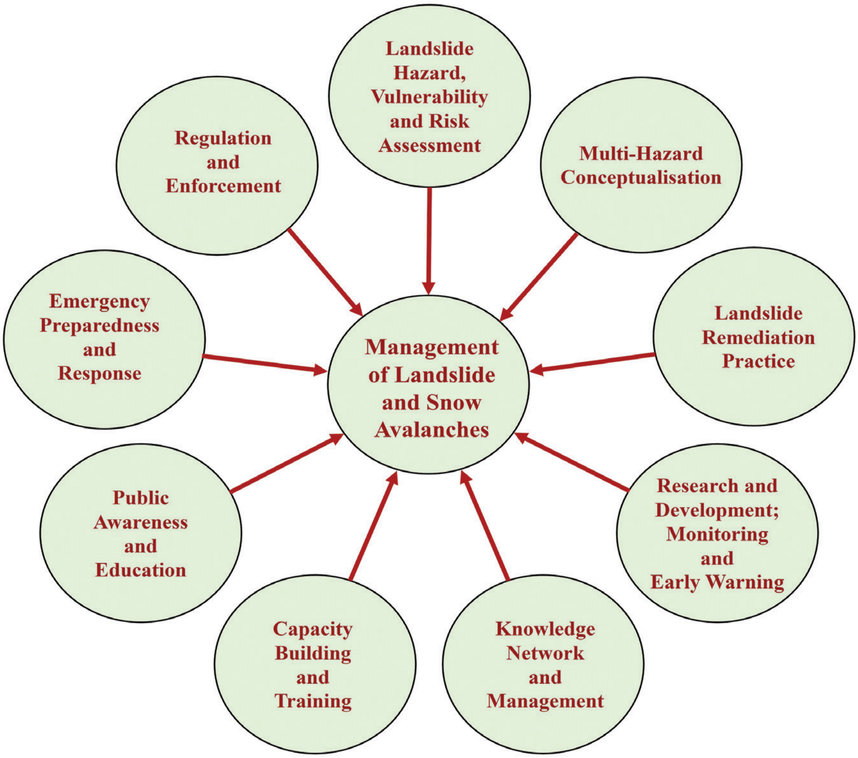
National Policy on Disaster Management, 2009

A National Policy on Disaster Management was formulated in the year 2009 with a vision to build a safe and disaster resilient India by developing a holistic, proactive, multi-disaster oriented and technology-driven strategy through a culture of prevention, mitigation, preparedness and response at all levels (NPDM, 2009). The policy exhorted mainstreaming disaster management plan in the development activities. Further, major emphasis was given on identification, assessment and monitoring of disaster risks; mitigation measures based on traditional knowledge, technology and environmental sustainability; forecasting and early warning systems; building disaster-resilient structures and efficient response and relief with a caring approach towards the needs of the vulnerable sections of the society.

Guidelines on Management of Landslides and Snow Avalanches, 2009

Apprehending the enormous destructive potential of the landslides and the need of reducing the resultant losses of lives and economy, National Disaster Management Authority, Government of India in the year 2009 materialised "National Disaster Management Guidelines Management of Landslides and Snow Avalanches". The guidelines incorporated time-bound regulatory and non-regulatory framework to institutionalise the landslide hazard mitigation efforts apart from enhancing the capacity of society to take appropriate measures to avoid/reduce the risks and costs associated with the hazard (National Disaster Management Guidelines, 2009). To address the challenges against the landslides risk reduction and resilience, nine major areas were acknowledged for systematic, synchronised and effective management of landslides hazards (Fig. 10.1).

Fig. 10.1: Major Elements for Effective Management of the Landslides



Source: National Disaster Management Guidelines, 2009

National Disaster Management Plan (NDMP), 2016 & 2019

To carry forward the bequest of Disaster Management Act 2005, National Policy on Disaster Management (2009) and to shoulder the current global best practices and knowledge in all the horizons of disaster management, the National Disaster Management Plan was formulated in 2016. The plan provides a framework and direction to all the government departments/agencies for all phases {mitigation (prevention and risk reduction), preparedness, response and recovery (immediate restoration and build-back better)} of disaster management cycle (NDMP, 2019). It was the world's first national plan line up with the Sendai Framework-2015. NDMP was revised in the year 2019 integrating rationality of Sendai Framework for Disaster Risk Reduction (SFDRR)-2015, Paris Agreement on Climate Change, Sustainable Development Goals (2015-30) and Hon'ble Prime Minister Ten Point Agenda on DRR.

NDMP adopted the classification system the catalogues natural hazard into five major categories and is used globally for the Sendai targets monitoring. As per the classification, landslides are placed in the hydrological category while landslides as a secondary hazard after any earthquake are kept in a geophysical group. The national plan provides a planning framework and directions to government's cross-sectoral departments/agencies under six thematic areas for each hazard. The thematic areas classified are Understanding the Risk, Inter-Agency Coordination, Investing in DRR-Structural Measures, Investing in DRR-Non-Structural Measures, Capacity Development and Climate Change Risk Management. Further, these thematic areas are divided into different sub-thematic areas. The activities mentioned in the framework are grouped under overlapping time frames concluding by 2022 (short-term), 2027 (medium-term) and 2030 (long-term).

National Landslide Risk Management Strategy, 2019

To address all the odd challenges of the landslides at national as well as local level, National Disaster Management Authority, Government of India formulated a strategic document that also accomplishes the fifth target of Sendai Framework for Disaster Risk Reduction (2015-30) i.e., Substantially increase the number of countries with national and local disaster risk reduction strategies by 2020 (NLRMS, 2019). National Landslide Risk Management Strategy laid recommendations on all the major components of landslide disaster risk reduction and management. The components which were focused are, landslide hazard mapping, monitoring and early warning system, awareness generation programmes, capacity building & training, mountain zone regulations & policies and mitigation of landslides & creation of special purpose vehicle for landslide management. The recommendations laid by the strategy document included:

- As most of landslide hazard zonation maps available are at a small scale (1:50000), they have limited efficacy in any development activities. Hence, the need of hour is to produce maps at macro and meso scale using advanced scientific state-of-the-art tools such as Unmanned Aerial Vehicle (UAV), Terrestrial Laser Scanner, and very high-resolution Earth Observation (EO) data.
- To foster the R&D for development of early warning system based on rainfall threshold, earthquake-induced landslide modelling and Wireless Sensor Network (WSN) based instrumentation.
- To promote the culture of awareness generation and preparedness by involving and educating the local communities especially the youth about the landslide management as well as other hazards of their respective areas.

- Identifying the target groups from national to the grass root level and enhancing their capacity for landslides risk reduction through training programmes having upgraded and simplified contents with new technological inputs.
- To review and revise existing codes/standards/uidelines for landslide management and to update and enforce building regulations and bye-laws by State Governments/ Local bodies.
- To identify most problematic landside sites and identifying suitable control measures for site-specific landslide stabilisation and mitigation of problematic landslides.
- To establish a national-level centre dedicated only for landslide research studies and management.

Initiatives Taken On National Interventions

A number of departments/institutes are working in the field of landslides risk reduction and resilience in the country. Geological Survey of India (GSI) under the Ministry of Mines is associated with studies of landslides since 1880. GSI was declared as the 'Nodal Agency' for undertaking research and development in the field of landslides management on January 29, 2004. The Gazette of India Notification dated September 25, 2012, constituted a Technical Advisory Committee (TAC) for Landslide Mitigation and Management to foster landslides related R&D in the field of mapping, monitoring and capacity enhancement. In 2014, GSI launched National Landslide Susceptibility Mapping (NLSM) programme to cover landslide prone areas of the country to create a dynamic National Landslide Susceptibility Geo-database, GIS-based seamless Landslide Susceptibility Maps and a nation-wide repository on GIS-based Landslide Inventory. The other achievements of GSI include collaboration with national and international organisations/institutes for the development of S&T for mapping, hazard risk assessment, instrumentations and early warning system.

Bureau of Indian Standards (BIS) published a number of codes and guidelines related to different facets of landslides such as landslide hazard zonation mapping, design and construction of various retaining walls, landslide control, selection of materials for residential buildings in hilly areas and national building code. Indian Road Congress (IRC) helped the stakeholders concerning landslides on highways and roads through their guidelines on landslides mitigation, prevention and correction. Building Materials and Technology Promotion Council (BMTPC) under Ministry of Housing and Urban Affair educed third addition of Vulnerability Atlas of India in 2019 that provides State-wise hazard maps and district wise damage risk tables for the whole country. Institutes/

organisations can be utilised given information and data in the Atlas for developing methodologies for mitigation and prevention.

In pursuance of the mandate of DM Act 2005 for capacity enhancement, National Institute of Disaster Management developed a training module on "Comprehensive Landslides Risk Management" beside face to face and online training programmes on landslides risk reduction and resilience.

Conclusion

The High Power Committee (1999) and Disaster Management Act 2005 were the milestones that set a robust comprehensive institutional framework of the disaster management in country. The national interventions taken for reducing the risks of landslides have boost the capacity of various stakeholders for effective management of landslides. Safeguarding of the slopes is not the responsibilities of a particular section. We need multi-hands to support to protect them. Though many initiatives have already been done against the national interventions yet we have to go a long way for building a resilient ecosystem. Some of the major points on which we have to work are establishment of a national level centre dedicated only for landslide research studies and management, large scale landslide mapping, considering landslide risks in development projects, pacesetter example of landslides management, developing robust early warning system and enhancing the capacity of local communities.

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Geotechnical Characterization of Kangra Valley Landslide

Swati Sharma* and A.K. Mahajan*

Abstract

This study presents the numerical simulation of slopes through the stability analysis of a major landslide which occurred on 14 August 2013 after a prolonged rainfall episode and affected the Tiralines village near Dharamshala city of district Kangra, Himachal Pradesh. The study involves the field investigations, a geotechnical study of the slope material's index properties and numerical modelling using 2D finite element method (FEM) for finding the cause and nature of the landslide. Three slope models have been used for the stability analysis in Phase[2] software. An external building load/force is applied in model 1 of the slope section 'A' whereas, for model 2 of the slope section 'A' no external building load was used. Model 3 for section 'B' is from the same landslide body representing the natural slope exposed after the first landslide episode. All the models were simulated for the critical strength reduction factor (SRF) beyond which the slope would fail. The results reveal a low critical SRF value 0.85 for model 1 at which the maximum displacement of 0.22 m was computed for the lower portion of the slope section 'A' which looks vulnerable. The SRF value 1.27 for model 2 and 1.15 for model 3 shows comparative marginal stability theoretically but, the field conditions indicate critical slope nature.

Keywords: Landslide; Characterization; Kangra; FEM

Introduction

Landslide is one of the main natural hazards leading to global economic as well as societal loss and this phenomenon has alone affected almost 15 per cent of the Indian landmass (Onagh et al., 2012) out of which maximum landslide events are restricted to the Himalayan region especially in the north and north-eastern parts. Many parts of

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the Himalayan region generally remain under stress due to the continuous northward movement of the Indian landmass causing dynamic tectonic activities (Sharma and Mahajan, 2018) leading to earthquakes, mass movements, subsidence, etc. The developmental activity in the Himalayan regions can only be accomplished with proper geological and geotechnical studies on large scale for safer constructions (Fall et al., 2006) however, most of the road and the settlements are worst hit due to landslide movements reflecting poor planning and applications of unscientific methods for planning constructions (Anabalgan et al., 2008). Natural slope stability in hilly regions is usually distorted due to the unplanned excavations for new constructions or widening of transportation routes, extreme climatic conditions such as a prolonged rainfall event or an earthquake in areas with structural discontinuities, vegetation patterns that slowly degrade the quality of slope material, etc. (Anabalgan et al., 2008), (Singh et al., 2014) and (Umrao et al., 2011). Considering the number of challenges faced by the Himalayan slopes, the stabilization process requires slope stability analysis and use of engineering applications. The stability of rock slopes or the debris slope depends on the inherent properties of the material (porosity, permeability, type of material, plasticity, shear strength) and the internal and external forces that are exerted on the slopes (Singh et al., 2016).

The detailed slope stability analysis for a landslide is categorised under the post-disaster evaluation of various geotechnical parameters and using them as input for simulating the actual slope conditions in computer-based programmes. Number of such stability analysis methods (limit equilibrium method) proposed by Janbu (Janbu, 1968), Bishop (Bisho, 1995), Morgenstern (Morgenstern and Price, 1965) and Spencer (Spencer, 1967) have been widely used which involve number of assumptions along with the problems of dealing with slope material heterogeneity and the varying slope geometry. In contrast to the limit equilibrium method, the numerical modelling approach like Finite Element Method (FEM) considers the slope material's homogeneity and inter-slice force determination for giving the factor of safety value for slopes (Kanungo et al., 2013) therefore, it is more efficient and preferred method due to its non-linear nature and ease of simulating the heterogeneous slope material and has been used by various researchers (Savage et al., 2000; Quecedo et al., 2004; Singh and Verma, 2007; Sarkar and Singh, 2007; Sarkar et al., 2012; Singh et al., 2013; Kanungo et al., 2013; Singh et al., 2013; Verma et al., 2013; Mahanta et al., 2016; Singh et al., 2016; Gupta et al., 2016 and Jamir et al., 2017). FEM is therefore much useful and now is coupled with the shear strength reduction method (Matsui and San, 1992) using the criteria of reducing the shear strength of the material (successive reduction of cohesion(c) and friction angle (φ) by a certain factor called shear strength reduction factor (SRF) as shown in Eqs. (1) and (2) till the slope failure occurs which is considered as the value of factor of safety (FoS) for the slopes.

$$c_f = \frac{c}{SRF} \tag{1}$$

where, c_f is the reduced cohesion factor

$$\Phi_f = \frac{\Phi}{SRF} \tag{2}$$

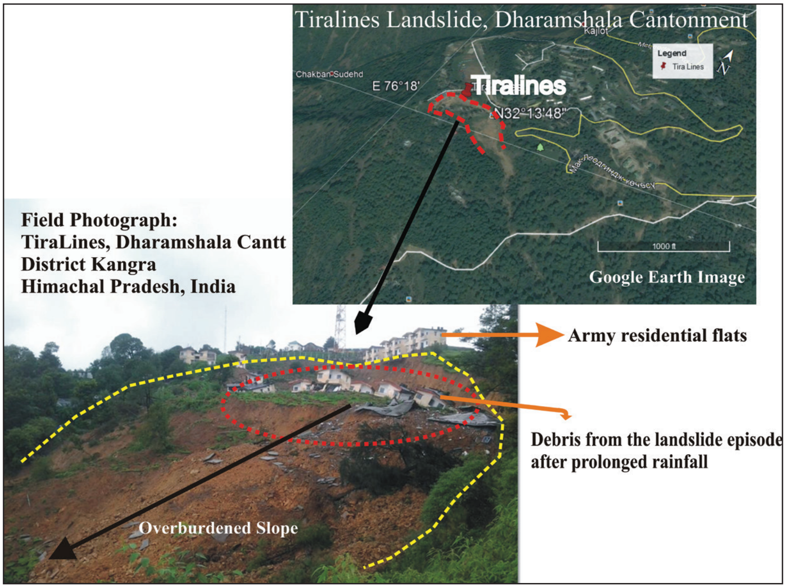
where, Φ_f is the reduced friction angle factor

In this study, 2D Finite Element Method (FEM) has been utilised for modelling the debris slopes of a major landslide in Tirah village near to Dharamshala town, Himachal Pradesh, India. The geotechnical properties of the slope material, the field studies and the previous literature data have been used as input in FEM modelling with the help of computer-based Phase^2 software (Rocscience, 2010) for the numerical simulations. Kanungo et al. (2013) described the failure criteria most suitable in FEM based studies i.e. non-convergence of solution within the user-specified iterations at a point of simultaneous slope failure and a similar approach was followed in this study. The landslide area under consideration is sandwiched between the major Thrusts namely Main Boundary Thrust (MBT) in the north and a local Drini Thrust/Murree Thrust in the south, making it tectonically very active (Mahajan and Kumar, 1994). This study highlighted the critical zones on the landslide site which have the highest stress accumulations that should be subjected to mitigation and continuous monitoring.

Study Area and Field Observations

The Tiralines landslide is located on Dharamshala-Mcleodganj road (32°13' N-76°19' E), almost 2.5 km from the main Dharamshala city in the district Kangra of Himachal Pradesh (Fig. 11.1). The general elevation of the Tiralines landslide is 1600 m a.m.s.l and fall on a survey of India toposheet number 52D/8. This landslide event occurred in the month of August 2013 situated in the Dharamshala cantonment which comes under wet-temperate zone with annual precipitation of 2900 ± 639 mm and the mean annual temperature of 19°C.

Fig. 11.1: Location of the study area



The Tiralines landslide is one of its kinds in this region as it destroyed almost 28 local and army residences after continuous downpour for 4 days in August 2013. The landslide affected area is mainly covered by debris and chunks of weathered rock material from the surrounding slopes. The landslide zone is underlain by Dharamsala Group of rocks constituting sandstones with alternating clays, shale and siltstone bands forming part of the Outer Himalayan zone. The sandstone is highly Feldspathic in nature and thus is highly moisture absorbing. Since the Dharamsala Group of rocks comprises three different lithology i.e. sandstone, claystone and siltstone; the impermeable claystone layer which is overlain by the debris material easily absorbs moisture during the precipitation events and provides an easy sliding plane leading to slope instability. The alternating sandstone, claystone and siltstone layers are highly weathered in the study area (Fig. 11.2). The detailed contour map of the landslide was prepared based on the total station survey method at the scale of 1:500 with 1m contour interval (Fig. 11.3) which shows the morphology of the landslide body. The landslide site was investigated for studying the various slope sections, type of mass movement and for the sample collections.

The Tiralines landslide is a potential debris slide and is situated less than 150 m away from the main road connecting the army cantonment area with other parts of the Dharamshala city. Towards the crown area of the landslide body are the buildings of army settlement few of which were badly destroyed because of the landslide event. The total affected area of landslide as mapped is 19062 m^2 which affected the nearby slopes and has increased the chances of future slope failure in its vicinity. The general slope angle of this landslide varies between 40° to 45° and the slope orientations vary between N 105° and N 145°. The landslide is located in the Dharamsala Group of rocks which has sandstone as the bedrock seen to be exposed in a small patch near to the landslide area and is highly weathered. The slopes have debris cover of almost 20 to 25 m which has been estimated based on field observations and also the bedrock was exposed somewhere 25 m south to the crown part of the landslide near the lateral side of local drainage. The overlying debris material on the slopes seems to be a product of weathering of the bedrock (sandstone) as it has sandy cobbles and pebbles which are very fragile and other parts of the debris material are the Quaternary glacial deposits. Numbers of lateral cracks were observed during the field studies which must have played an important role in the sliding event as the damage occurred after a prolonged rainfall episode and the cracks or the fissures remain the easiest path for water to percolate sub-surface.

Fig. 11.2: View of the Tiralines landslide from August 2013 showing amount of damage and the latest view of the area showing the settlements just above the damaged slope

Methodology

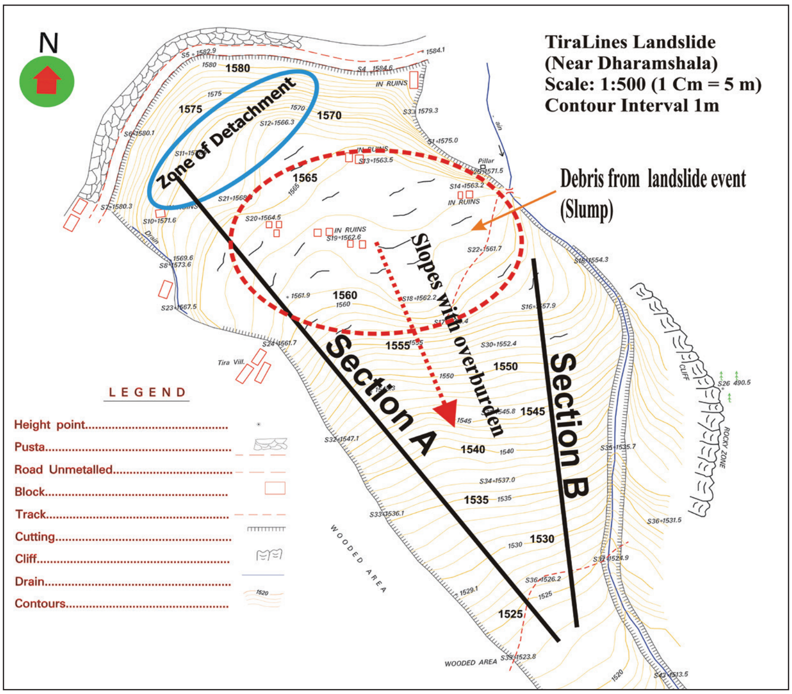
Field investigations were carried out at 1:500 scale as shown in Fig. 11.3, to study the type of the slope material movement. The arbitrary latitude-longitude and the corresponding elevation values were recorded using the total station method (Table 11.1) which resulted in the detailed map of the landslide site that was geo-referenced using the global positioning system (GPS) points recorded during the field survey. The landslide falls under army jurisdiction where any kind of scientific drilling was not permissible. The landslide site was then investigated for studying the various slope sections, type of mass movement and sample collections. From the landslide body, two slope sections (sections A and B) were chosen for the slope stability analysis. The choice of these slope sections was based on their potential steepness and elevations which create the possibility of future landslide episode under similar physical/ climatic conditions that triggered the slope failure under study. The collection of the representative samples from the landslide body was performed in order to find out their index properties for using in the computer-based finite element modelling in the Phase[2] (version 6.0) software.

Table 11.1: showing total station survey readings (Latitude-Longitude and Elevations) for detailed mapping of the Tiralines landslide

Arbitrary Latitude	Arbitrary Longitude	Elevation (m)
1000	2000	500
1007	2000	501.2
1009.004	1993	504.259
1021.33	1983.154	509.578
1027.189	1927.32	507.941
1001.963	1911.401	505.443
979.573	1904.249	505.293
961.436	1916.742	498.591
962.93	1921.122	494.602
975.042	1917.953	496.57
994.05	1926.081	496.503
1005.615	1951.497	491.332
994.398	1980.091	488.946
986	2009.527	488.248
963.325	2044.356	479.308
948.611	2028.695	482.937
944.226	2004.988	484.376
951.486	1995.523	487.399
970.809	1971.089	487.586
976.772	1948.947	489.939
982.352	1939.822	493.517
966.142	2014.691	486.701
948.052	1923.921	492.547

937.319	1952.91	486.744
991.568	2015.082	496.146
922.426	2084.847	490.472
936.384	2017.663	477.383
915.006	2017.806	470.759
907.96	1971.776	472.115
883.258	1985.456	461.878
894.967	2017.387	462.045
904.312	2052.778	460.683
881.545	2066.115	456.482
869.003	2050.718	449.944
862.147	2030.312	451.178
838.582	2023.289	448.832
822.193	2046.137	444.081
796.565	2076.796	428.666
811.822	2085.398	431.964
832.116	2067.076	438.489

Fig. 11.3: Contour Map of the study area at a scale of 1:500 & 1m contour interval (inset slope sections A and B for the stability analysis)



The soil samples representing the actual slope material were collected from different parts of this landslide body from a depth of almost 1 m beneath the surface: sample I from the area near the zone of detachment (top), sample II from the area near to the middle of the landslide body and sample III from the area near to the toe of the landslide body (bottom). These representative soil samples were stored in the air tight plastic bags and were transported to the laboratory for determining their geotechnical properties (as per standard procedures) such as grain size distribution, dry density (gm/cm^3), liquid limit (per cent), plastic limit (per cent), permeability (cm/sec), cohesion (kPa) and friction angle (°). Also, the field density (gm/cm^3) of slope material was determined at the sites of the sample collection. Two slope sections A and B were chosen from the detailed map of the landslide (Fig. 11.3) to prepare the slope models representing their geometry and vulnerability towards the future sliding event. The slope sections of the landslide for using in the slope modelling were extracted from the ASTERGDEM data of 30 m resolution (obtained from USGS website https://earthexplorer.usgs.gov/). The determined material properties from the geotechnical lab studies were incorporated in the numerical simulations carried out with help of 2D finite element method (FEM) for the chosen slope sections.

Geotechnical Properties of Slope Material

Geotechnical properties of the slope material evaluated for the study are Grain size analysis, field density, dry density, optimum moisture content, liquid limit, plastic limit, specific gravity, permeability, cohesion and the friction angle.

Grain size analysis (Sieve method) and soil consistency

This test determines the per cent distribution of various grain sizes (coarse, medium and fine grain) in the soil samples. The soil sample collected was sun-dried, sieved and the grain size analysis was carried out as per BIS (1985) IS 2720 (Part 4). Fig. 11.4 represents the grain size distribution curves for the analyzed soil samples according to which they were classified.

The soil consistency indicates the firmness of the soil and its behaviour at various water contents (Koner and Chakravarty, 2016) which is represented as the Atterberg limits of the soil. Table 3 shows the values of LL, LP and Ip derived as per Indian Standard {BIS (1985) IS 2720 (Part 5)} and indicated maximum plasticity in sample 2 (Ip = 14.6%) whereas sample 1 indicates least plasticity (Ip = 2.2 per cent).

Overall the analysed soil samples reflected the majority of sandy composition i.e.

76.5 per cent to 82.4 per cent followed by the silt and clay mixture varying from 9.5 per cent to 12.1 per cent and lastly the gravels ranging between 8.1 per cent to 11.4 per cent. As shown in Table 11.2, sample-1 with 11.4 per cent gravels, 76.5 per cent sand and 12.1 per cent silt + clay mixture is classified under silty sand (SM) category as per unified classification method {BIS (1970) IS 1498}. Following the similar soil classification method for sample-2 (82.4 per cent sand, 8.1 per cent gravel and 9.5 per cent silt + clay mixture) and sample-3 (79.5 per cent sand, 10.2 gravel and 10.3 per cent silt clay mixture) were classified as SW-SM (well-graded sand to silty sand) and SP-SM (poorly graded sand to silty sand) respectively.

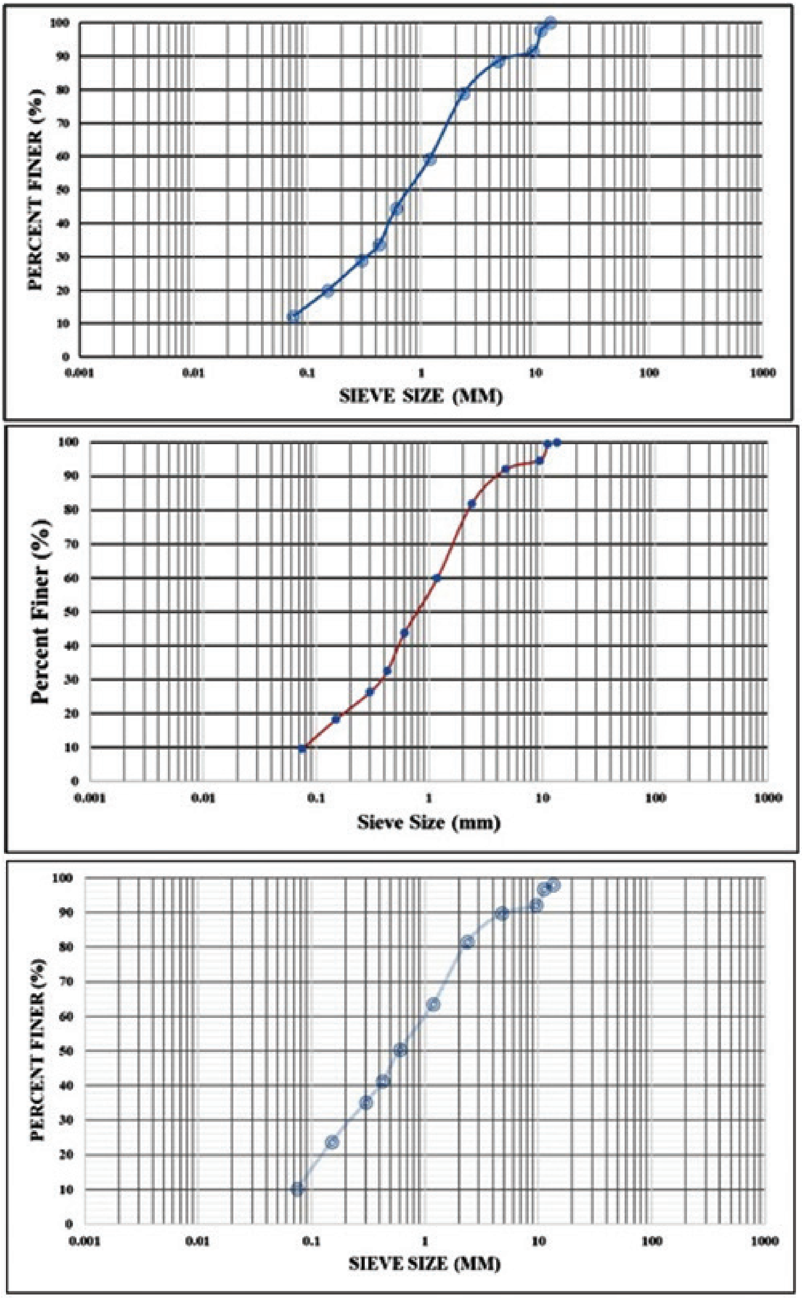
Table 11.2: Grain size distribution and classification of the soil samples

Grain Size Analysis	**Sample 1**	**Sample 2**	**Sample 3**
Composition	Gravel 11.4% Sand 76.5% Silt + Clay 12.1%	Gravel 8.1% Sand 82.4% Silt + Clay 9.5%	Gravel 10.2% Sand 79.5% Silt + Clay 10.3%
Cu (coefficient of uniformity)	11.11	14.44	14.29
Cc (coefficient of curvature)	1.78	1.37	0.89
Soil Classification (Unified System) As per IS 1498	SM (Silty Sand)	SW-SM (Well graded sand to Silty Sand)	SP-SM (Poorly Graded Sand to silty sand)

Table 11.3: Atterberg limits of the soil samples

	Liquid Limit (%)	**Plastic Limit (%)**	**Plasticity Index (%)**
Sample 1	22.9	20.7	2.2
Sample 2	23.1	8.5	14.6
Sample 3	19.5	15.3	4.2

Fig. 11.4 Grain-size distribution curves of sample 1 (top), sample 2 (middle) and sample 3 (bottom)



Permeability (K) and optimum moisture content (OMC) of the soil samples

In this study as all the soil samples were medium to fine-grained therefore falling head permeability test method was used to check their hydraulic conductivity as per Indian Standard {BIS (1986) IS 2720 (Part 17)}. The permeability (K) was measured as per the Eq. (3):

$$K = \frac{2.3\ al}{A(t_1 - t_0)} log_{10} \frac{h_0}{h_1} \qquad (3)$$

Where, K is the permeability, a is the cross-sectional of area vertical cylinder, l is the length of a cylinder which is connected to a stand pipe of cross-sectional area A, the water level is set at a height h_0 at time t_0, when the water starts draining into the sample water level falls at h_1 at time t_1 the water head drop was measured as $h_0 - h_1$ whereas, the time elapsed to drop the water head was noted as $t_1 - t_0$.

Table 11.4 shows the permeability range of the samples analysed from the study area which varies from 4×10^{-5} cm/sec to 4.66×10^{-5} cm/sec.

The field density (in-situ) of the soil samples were determined based on Indian standard {BIS (1975) IS 2720 (Part 29) and Table 11.4 shows the field density (gm/cm^3) of the tested samples. The dry density of the soil samples and the optimum moisture contents (OMC) were determined using modified proctor compaction methods as per Indian Standard {BIS (1983) IS 2720 (Part 8)}. The bulk density of the soil sample (γ) is calculated as per the Eq. (4):

$$\gamma = \frac{(W2 - W1)}{V}\ \text{gm/cm}^3 \qquad (4)$$

W_1 & W_2 are the weights of a sample, (W) is the moisture content, V is the volume of the cylindrical mould

The dry density γ_d was calculated as per Eq. (5):

$$\gamma_d = \frac{100\ \gamma}{(100 + W)}\ \text{gm/cm}^3 \qquad (5)$$

where, W is the moisture content and γ is the bulk density of the soil samples

Number of such determinations of dry density and moisture content were made and plotted on a graph where, the peak point on the graph corresponds to the optimum moisture content (OMC) of the soil samples. Table 11.4 shows the values of dry density and the OMC of the soil samples analysed.

Table 11.4: Geotechnical properties of the representative soil samples from the Tiralines landslide

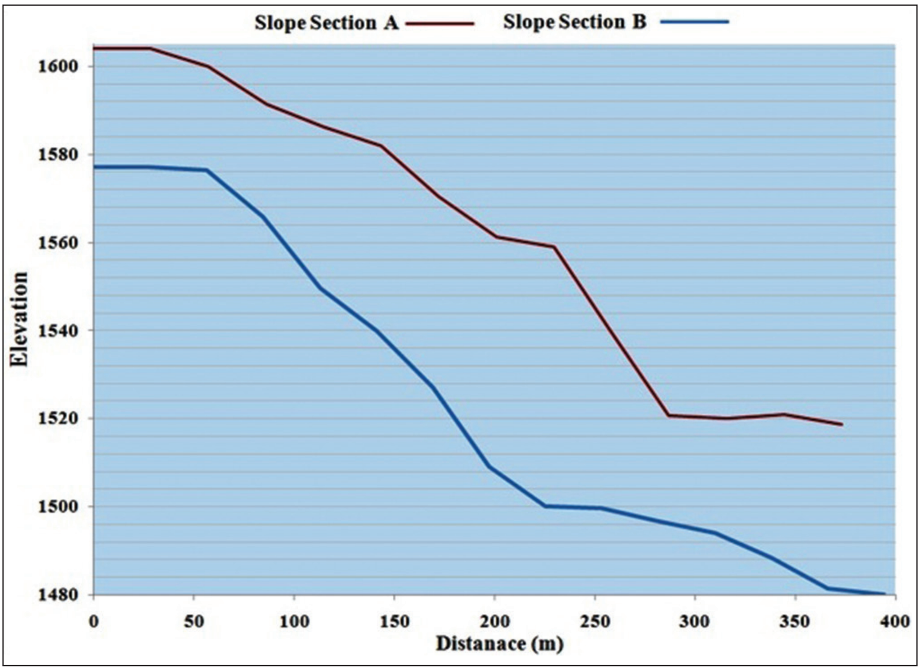
Material Properties	Field Density(gm/cm³)	Dry Density (gm/cm³)	OMC (%)	Permeability (cm/sec)	Cohesion (kPa)	Friction Angle (°)
Sample I	1.24	1.35	17.5	4.66×10^{-5}	0.07	25
Sample II	1.66	1.76	15.3	4.66×10^{-5}	0.02	27
Sample III	1.8	1.83	15.4	4×10^{-5}	0.17	31

Shear strength parameters

The shear strength of the soil is considered as the strength of sample to resist change till the point of failure. To derive the shear strength parameters, which are cohesion (c) and friction angle (Φ) direct shear test method was performed as per Indian Standard {BIS (1986) IS 2720 (part 13)}. The soil samples were prepared in a shear box of 6 cm × 6 cm dimension in a remolded form. The resulting values of cohesion and friction angle for the analysed samples are shown in Table 11.4.

4 Numerical simulations using finite element method (FEM)

Fig. 11.5: Slope section A and B extracted from the DEM data for using in the finite element modelling phase showing the slope geometry



In this study Phase2 software was used for FEM based continuum analysis for which the slope section A and B on the landslide zone were marked (Fig. 11.5) with the help of 30 m resolution digital elevation model DEM. First, the slope sections were imported into the Phase^2 software for finite element analysis and then were discretised into a finite number of domains (Fig. 11.6) without any set dimensions or pre-assumption of the slip surface shape or depth (Jing, 2013). The slope section domains are connected to each other with nodes and the forces are applied on these nodes which cause various interactions while the modelling. This modelling method records the strength reduction factor (SRF) values for the slope material at progressive strength reduction (SSR) (reduced cohesion 'c' and friction angle ϕ until the failure occurred Three slope models (Fig. 11.6) were used for stability analysis out of which for the slope section A, two types of scenarios were studied: slope model 1 with external building load and slope model 2 without external building load. The slope model 3 was analysed for section B on the landslide body which was without any external load and represented a separate lower portion on the landslide body vulnerable to sliding because of its observed geometry and overburden from the previous sliding (August 2013) in section A. All the slope models represented heterogeneous material i.e. overlying debris material on slopes and the basement rock i.e. sandstone. The material properties of the sandstone were taken as the standard value (Marinos and Hoek, 2000) and (Cai et al., 2004) as drilling was not performed to collect the core sample till the basement rock. For the overlying soil cover, lab investigations of the geotechnical properties and standard values for elastic modulus and Poisson's ratio by Gercek (Gercek, 2007) and Hoek et al. (Hoek et al., 2002) were used. This analysis involves the use of Mohr-Coulomb failure criteria (Janbu, 1968) for upper debris soil material and Hoek-Brown generalized criteria for the basement rock (sandstone) (Table 11.5). The slope was discretised into uniform mesh of two dimensional- 6 nodded triangular elements in three of the slope models. For slope model 1 and 2 overall 1974 elements were created to mesh the slope which has 4101 nodes and the mesh quality was ensured as only 23 mesh elements out of 1974 were of low quality which is only 1.2 per cent of the total elements. The slope model 3 (slope section B) was meshed with 1375 elements connected with 2902 nodes and only 1.1 per cent elements of low quality. The boundary conditions of the slope models were fixed (no displacements) on lateral sides and the bottom of the slope models, whereas kept free for the upper slope surface. The slope models were then subjected to loading i.e. only the body force (gravity load) in case of model 2 and model 3 whereas, gravity loading along with the vertical stress (external uniform building load) were applied for model 1. All the material properties were incorporated appropriately for the slope materials (overburden debris soil and sandstone) and the finite element modelling was run for shear strength reduction of the material till the critical strength reduction factor (SRF) was achieved.

Fig. 11.6 Finite element models 1 & 2 for slope section A of Tiralines landslide (model 1 with building load and model 2 without external load), model 3 for section B used in Phase2 software

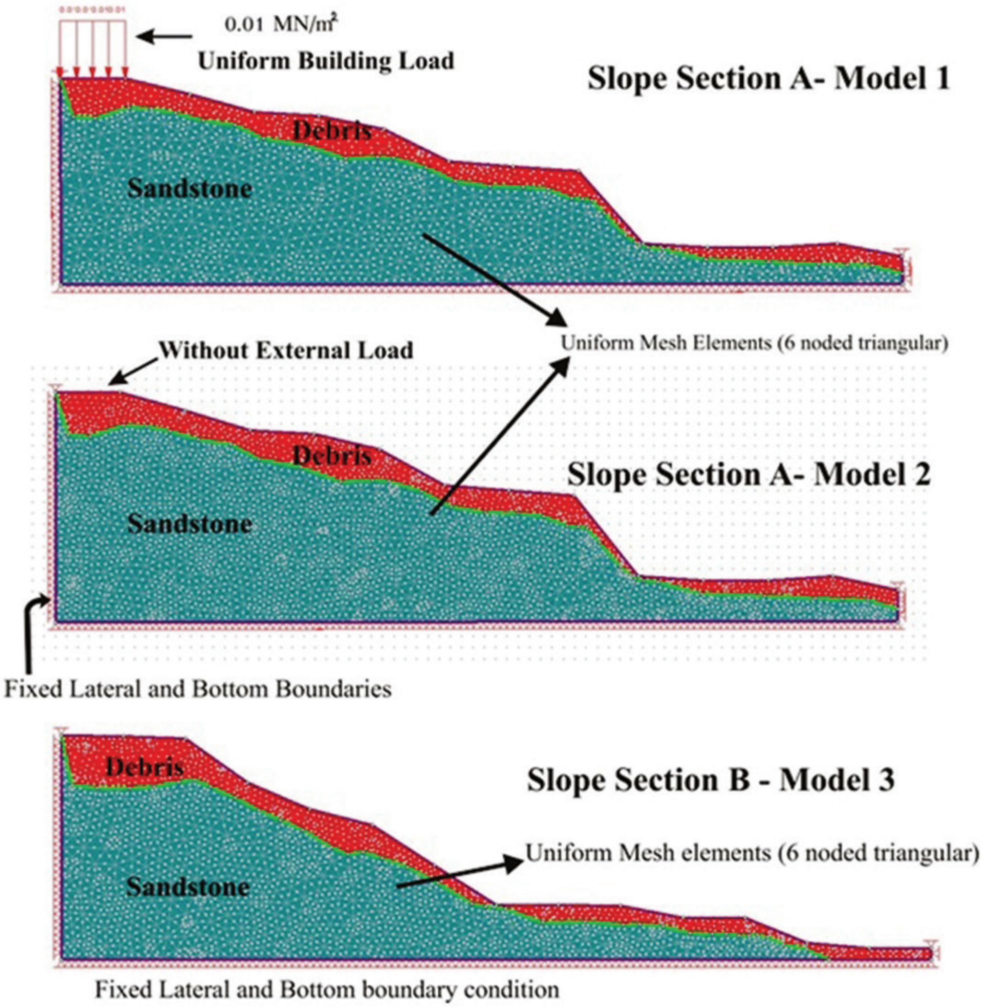


Table 11.5: Failure criteria for various slope materials and their properties used in finite element (FEM) continuum modelling, Kanungo et al. (Quecedo et al., 2004)

S. No.	Material	Model
1.	Overburden (Debris)	**Mohr-Coulomb,** (Gercek, 2007) $\tau = c + \sigma tan\varphi$ Where, τ is the shear strength of slope material, c and Φ are the shear strength parameters Initial element loading = Field stress and Body force Dilation Angle = 0 (natural slope), Hoek et al. 2002 Unit weight = 0.0205 MN/m^3, Poisson's ratio (υ) = 0.28, Young's Modulus = 20 MPa, Elastic type = isotropic
2.	Sandstone	**Generalized Hoek & Brown,** Marinos and Hoek, 2000 and Cai et al., 2004 $\sigma_1 = \sigma_3 + \sigma_{ct}\left[m_b\frac{\sigma_3}{\sigma_{ct}} + s\right]a$ σrepresents the principal stresses, Where, m_b is the reduced value of the material constant $m_{i,}$ Constant s and a, depend on the property of the rock type. Dilation Parameter = 0 (natural slope) Element Loading = Field stress and Body force Unit weight = 0.027MN/m^3, Poisson's ratio = 0.3, Young's Modulus = 20,000 MPa, Elastic type = isotropic, GSI = 50 MPa, a = 0.5, s = 0.0001, mb = 0.3

Results and Discussion

For discretised and meshed slope models 1, 2 and 3 (Fig. 11.6) shear strength reduction (SSR) analysis was carried out using Phase^2 software, in which the stresses were applied on each uniform mesh element. This finite element modelling (FEM) determined the critical strength reduction factor (SRF) values using plain strain analysis for each slope model and the maximum displacement of slope material at that critical SRF values (Fig. 11.7). The numerical simulation results (Table 11.6) for model-1 of slope Section-A reflected critical SRF value of 0.84 with a maximum displacement of 0.35 m at this SRF.

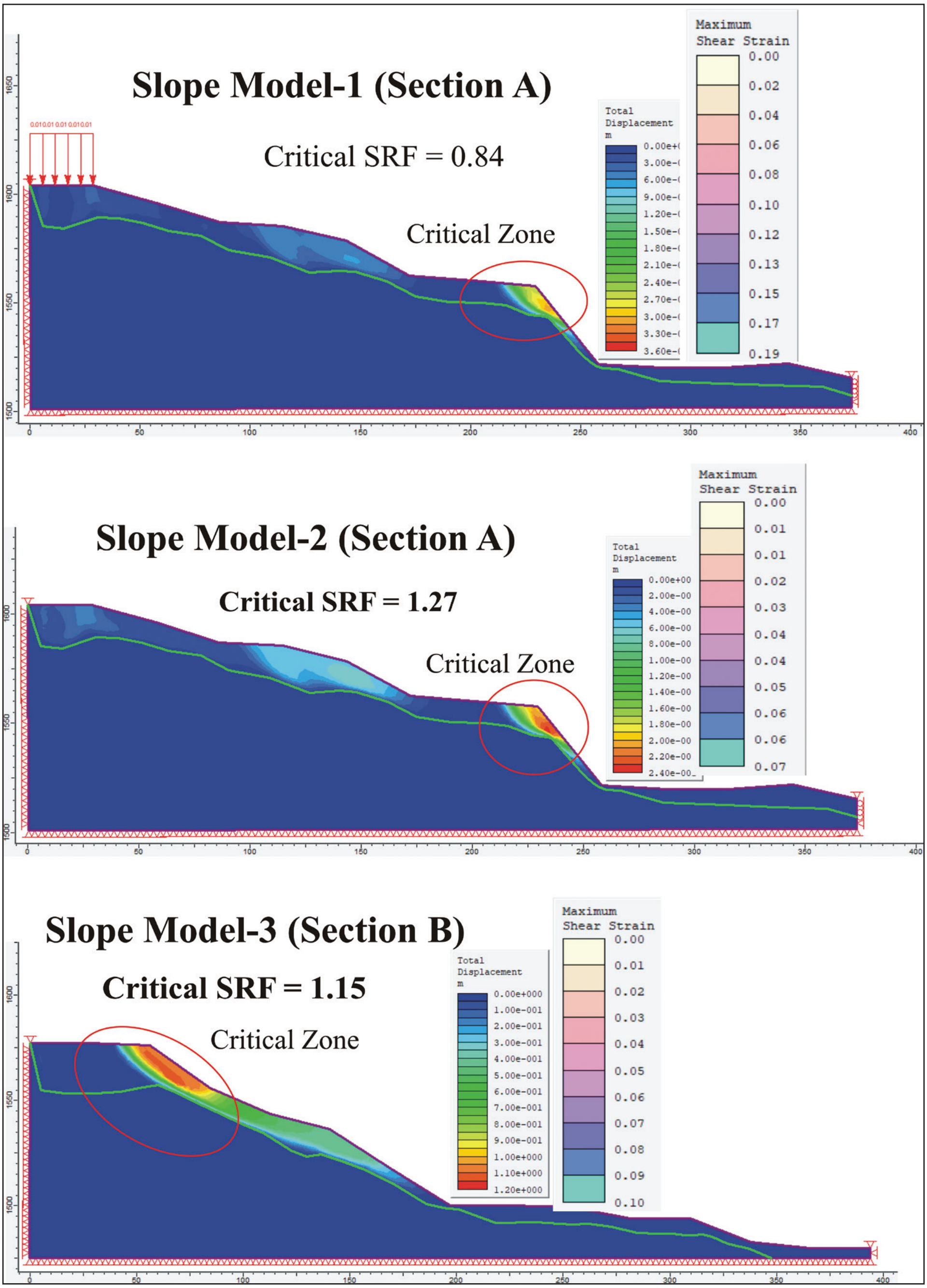
For slope model-2 of Section-A without external loading, the critical SRF value 1.27 with a maximum displacement of 0.2 m resulted. Model-3 for the slope Section-B has shown a critical SRF value 1.15 with maximum displacement value of 0.84 m. The Section-B had much steeper slope from the middle to lower parts whereas, the crown area seems to be in stable condition because of its geometry which resulted in marginal stability value of 1.15. The results for the slope Section-A of the Tiralines landslide with building load (model-1) resulted into SRF value 0.84 which reflected its unstable condition. This clearly indicates that the slope material had low shear strength to bear the load of multistoried settlements and the added impact of the prolonged rainfall event in August 2013 led to the massive mass movement that destroyed many houses. Obviously, with the previous settlements on this weak slope, the domestic drainage and the sewerage system were also unscientifically constructed and the water kept seeping through this weak slope material and led to the ultimate slope failure.

Table 11.6: Results of the FEM based modelling for slope Sections A and B

S. No.	Strength Reduction Factor (SRF)	Maximum Shear Strain	Maximum Displacement (m)
Model 1 (Section A)	0.84	0.19	0.35
Model 2 (Section A)	1.27	0.07	0.20
Model 3 (Section B)	1.15	0.10	0.84

The slope model-2 for section-A of the landslide shows SRF value 1.27 which indicates the marginal slope stability as reflected in Fig. 11.7, the steep downhill side of the slope shows maximum displacement of material. The uphill side of slope section A is mainly covered with debris from the previous landslide also but the lower side of the slope being steeper can fail due to overburden pressure. Maximum displacement for slope models 1 and 2 is indicated at the lower parts of the slope, highlighted with the bright critical zone (Fig. 11.7).

Fig. 11.7: Shear strength reduction (SSR) results for slope models showing the critical SRF values



The maximum shear strain value for the slope model-1 is highest showing an agreement with its low value of critical strength reduction factor (SRF) 0.84. The results show agreement with the field conditions accurately as while the field studies the critical slope behaviour was much obvious with the observation of lateral cracks, water seepage from nearby seasonal drainage and tilting of shrubs on the slopes. Therefore, keeping in view the critical zones on the slope sections of models 1, 2 and 3 instrumentation for monitoring the future landslide activities and mitigation of present problems can be suggested. This landslide site is very sensitive as the debris from the first mass movement in 2013 were cleared off towards the toe area of the hill slope which has increased the overburden pressure and this can lead to another sliding episode in future.

This study on the detailed scale (1:500) for the Tiralines landslide near the Dharamshala city has helped in representing the slope problems and the local causal factors leading to the destruction of infrastructure or transportation routes in such a developing area. The study has revealed the geotechnical properties of the slope material in detail indicating the sandy composition of the overlying slope material which reflects the coarser grain size with small amount of fines (clay + silt) that can allow higher permeability of water into the slope and thus increasing the pore pressure leading to the slope instabilities.

The samples analysed in this study have shown low liquid and plastic limit values for the soil with sandy and lesser fines classification. This mainly indicates the phenomenon that led to the easy water percolation into the slope sub-surface mainly composed of weathered by-products of the sandstone i.e. poorly to well-graded sandy plus silty soil. The dry density values increased for the sample collected from the crown (sample I), middle parts (sample II) and the toe region (sample III) of the landslide body respectively which revealed that the slope material from the upper parts was less compact with more void ratio (higher moisture content) whereas the soil from the middle and toe portions were more compacted with higher dry density and lesser void ratio. The coefficient of permeability values calculated for the soil samples in this study ranged between 4 and 4.66×10^{-5} cm/sec which indicated the presence of sand with gravelly compositions and little amount of fines which was also proportionate with the analysed grain size values. All these results from the geotechnical investigations revealed that the nature of the slope material from the study area could not bear the increased pore pressure due to the prolonged rainfall episode along with the added load of the multi-storey buildings on it. This primarily indicated the nature of slopes from the overall Dharamshala region with debris soil materials overlying the basement rocks, which will not remain stable due to heavy rainfall, unplanned installation of the sewerage systems or the water reservoirs in this hilly terrain. Therefore, the overall results from the geotechnical and the FEM based stability analysis study show the marginal to low slope stability at increased soil moisture due to climatic or anthropogenic interference.

Conclusion

The numerical modelling methods for slope stability analysis has evolved as one of the most powerful tools for suggesting mitigation measures post-disaster and can indicate the zones of slope sections that require immediate attention to avoid future landslides. In this study, the finite element method (FEM) was utilized for modelling the debris slopes of Tiralines landslide of near the Dharamshala city of Himachal Pradesh which occurred in the monsoon of 2013 and destroyed many army residential settlements. This study has determined the critical shear strength reduction factor (SRF) and the corresponding maximum displacement values along with the maximum shear strain for the three slope models. The 2D continuum modelling has shown results in agreement with the actual field conditions as the critical zones highlighted on the slope models represent sensitivity towards sliding on the actual ground as well.

- The results have shown the impact of building load on weak slope material in model 1 which has already failed in 2013 Tiralines landslide event. The slope models 2 and 3 indicate marginal stability of the existing slopes because of the overburden pressure from the massive debris of the previous landslide.
- The geotechnical characterization reflected coarse-grained and high permeable nature of the slope material at the landslide site.
- The investigated results from a geotechnical study of the soil from Tiralines landslide can be extrapolated to determine the nature of slope failure of other landslides in its vicinity.

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