Study of qualitative stability analysis and rainfall thresholds for possible landslide occurrence: a case study of Sikkim Himalaya

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ABSTRACT

Landslide hazard characterization in the Setijhora landslide, located near Kalijhora village, along National Highway 10, was carried out in a qualitative way using Rock Mass Rating (RMR), Continuous Slope Mass Rating (CSMR) and Geological Strength Index (GSI). CSMR data helped in the understanding of slope failures (wedge, planner, rotational and toppling), while RMR & GSI data provides a better understanding of rock mass quality and its deformation. RMR was observed between 10–49 in the dry season and 1–39 in the monsoon season. Kinematic/stereographic analyses indicate vulnerability to wedge failure, while CSMR ranges from 13.84 to 50.85 (class III to class V). Rainfall threshold data shows cumulative rainfall of more than 111.3 mm over 20 days and 222 mm in a month indicating a high probability of landslides occurrence. Data generated from the study will be very useful for developing landslide early warning in the study area.

1. Introduction

Landslides pose a severe hazard to civilization in the mountainous terrain. A landslide in an uninhabited region causes no threat because it’s a natural phenomenon that would be checked and balanced by nature itself. But landslides in an inhabited region pose a severe threat as it can lead to massive loss of human lives and infrastructures. Human society in mountainous regions often faces grave danger from landslide disasters triggered both due to unsustainable poorly planned anthropogenic activities and other natural triggers [1–4]. Road networks in the hilly regions are constructed by excavating mountain slopes. Inadvertently the excavation for road construction and widening projects is carried out using inefficient construction techniques, where essential geological and geotechnical factors that cause slope instability are overlooked [5–10].

Slope stability is controlled by multiple factors viz. the rock types (lithology), disposition and types of structural discontinuities, rainfall, weathering index of litho-units, overall relief of terrain, seismic zonation, construction of megastructures (dams/reservoirs/tunne lls/mining), etc. [11–13].

Primarily slope failures occur, when the critical threshold limit prescribed by prevailing structural discontinuities in rocks, nature of the slope forming material and other geological and geotechnical parameters is exceeded. All major Himalayan road networks particularly those manifesting close to major regional tectonic discontinuities like Main Central Thrust (MCT), Main Boundary Thrust (MBT), are threatened by landslides [14]. Thus it is imperative to analyse the slope stability and landslide vulnerability along all important roads. As per National Disaster management agency (NDMA), approximately 15% area of India is landslide prone, this includes the Himalayan mountain regions, the Shillong Plateau and the Western Ghats [15]. During the monsoon season, these regions experience frequent landslide events usually triggered by extreme climate events like high rainfall, cloud burst, GLOF, etc. and occasionally by a high magnitude seismic event. In India, landslide hazard-prone area excluding the snow-covered areas is estimated to be approximately about 0.42 million square kilometers or 12.6% of land area. Out of which, 0.18 million square kilometers or 47% area belongs to North Eastern Himalayas that includes Darjeeling and Kalimpong districts of West Bengal and the state of Sikkim. The northern districts of the state of West Bengal and the state of Sikkim lie in the seismically very active zone of the Eastern Himalaya possessing higher vulnerability to frequent landslides [16]. Along the national highways of Sikkim Himalaya, 27.39% of the total stretch comes under very high and high landslide susceptibility [17]. The whole Sikkim Darjeeling Himalayan roads face grave danger of landslides hazard around the year which amplifies during the monsoon period. The types of landslides vary with the
geological formation on which it is occurring. Higher grade rocks with a greater number of discontinuities are prone to rockfall and wedge failure. Whereas lower grade phyllitic rocks are more prone to planar sheet failure. Lower-grade meta-sediments and phyllites are also easily weathered out and make huge accumulation of debris during rainy days. The weathering nature of rocks aggravates the problem of slope instability.

Rainfall is the major factor influencing and triggering landslides. Rainfall thresholds for landslide initiation can be estimated via physical and/or empirical criteria [18]. Physical threshold models provide detailed spatial information on the lithological, morphological, hydro-geological and soil strength characteristics that control the initiation of the landslide. These models predict the threshold amount of precipitation required to trigger failure, along with the location and time of the expected landslides.

Physical threshold models are process-based models that link slope stability models through the incorporation of infiltration models by correlating regional rainfall patterns and historical slope failure events. Empirical rainfall threshold models are established by studying events that have caused landslides. These thresholds are estimated by establishing lower-boundary lines to the rainfall conditions that have resulted in landslides, and are plotted in Cartesian, semi-logarithmic, or logarithmic coordinates. Empirical thresholds, for initiation of landslides are classified into global, regional or local thresholds. Global threshold represents a general or universal minimum level of rainfall below which landslides do not occur, and these are independent of local morphological, lithological and land use conditions or regional rainfall pattern and history [18]. Global thresholds have been proposed by Cannon and Gartner [19].

Regional thresholds are defined for areas extending from a few to several thousand square kilometers of similar meteorological, climatic and physiographic characteristics [20,21]. While the local thresholds are established by considering the local climate regime and geomorphological setting, and they focus on single landslides or to a group of landslides extending from a few to several hundreds of square kilometers such as in a basin, a highway corridor, etc. Empirical rainfall thresholds are classified into three categories, based on the type of rainfall measurements: (1) thresholds that combine precipitation measurement obtained for a specific rainfall event. (2) Threshold that considers the antecedent conditions, (3) other thresholds, including hydrological thresholds. Thresholds based on rainfall measurements are further subdivided into four subcategories: (i) intensity-duration (ID) thresholds, (ii) thresholds based on the total event rainfall, (iii) rainfall event-duration (ED) thresholds and (iv) rainfall event-intensity (EI) thresholds.

The whole west to east stretch of Himalayan Mountain belt habitats where high landslide activity in the monsoon season poses threat, are yet not well covered in terms of studies concerning the understanding of regional and local rainfall thresholds for landslides events. Rainfall threshold studies in Darjeeling Himalaya were carried out by Dikshit and Satyam [22]. Kanungo and Sharma [23] established rainfall threshold for landslide initiation in Garhwal Himalaya. Kuthari [24] established rainfall threshold in Alakananda Valley. In Sikkim, precipitation threshold was evaluated by Sengupta et al. [25]. The threshold of precipitation for the initiation of landslide in this study has been evaluated using statistical analyses methods [22,25,26] considering temporal rainfall data and landslide inventory. Studies also suggest that the use of geosynthetic material on roads [27] not only prevents damages but also can stabilize steep slopes and is useful in water management also [28].

The current study focused on the Setijhora landslide, along NH 10 in Darjeeling district of West Bengal, India, which is highly vulnerable to landslides (Figure 1). The major objective of the present study is analysing the vulnerability of slopes to landslide and studies the factors that can trigger the landslide in future.

Geotechnical and kinematic aspects of the sliding mechanism along with the variation of rock mass strength across the extent of the landslide were studied. The determination of geotechnical as well as geological parameters viz., volumetric joint (Jv), rock quality designation (RQD), rock mass rating (RMR), continuous slope mass rating (CSMR) and geological strength index (GSI) along the lateral extent of the slide was carried out. Various orientations of discontinuities were analysed using the stereographic projection technique to understand the type of mass movement. The outcome of this study will be very helpful in making the landslide hazard zonation map of the study area using generated data and in the implementation of landslide mitigation strategies.

2. Study area

The study area selected is along NH-10, Setijhora, located (Figure 2) North of Kalijhora town, beside the river Teesta, in the Darjeeling district of West Bengal state in eastern India. This road is a lifeline for the hill districts of Darjeeling, Kalimpong and the state of Sikkim. There is no rail or effective air connectivity in this region. The road also bears the burden of heavy transport operated by Indian defense forces, engaged along the borders of Sikkim. Darjeeling district is bounded by latitudes 26°26´48.53´´ to 27°12´44.9´´ and longitudes 88°0´30.25´´ E to 88°53´59.08´´ E and covers an area of 3143 square kilometers. The district is bordered by Sikkim, Nepal and Bhutan in the north, west and east respectively. At the south lies the Purnea District of Bihar and west Dinajpur district of West Bengal. The Darjeeling and Kalimpong hill area is formed of comparatively recent rock structures, viz. sheared tectonic.
Figure 1. Field photographs of (A) toe erosion, (B) pilling up of debris from the body of the landslide in monsoon season, (C) multiple fracture orientations, (D) boudinized quartz vein, (E) NH-10 bisecting the landslide, (F) panoramic view of river bend of the affected area.

meta-sedimentary rocks. Relief varies from 100 m to 2590 m above mean sea level. The moist tropical climate is experienced in the study area as it lies at an altitude of 250 m. Because of the proximity to the Bay of Bengal and exposure to the effects of summer monsoon, Sikkim-Darjeeling region is one of the most humid areas in the Himalayas.

2.1. Background of the study

National Highway 10 connects the state of Sikkim with the rest of India via state of West Bengal. The transportation is often severely hampered by numerous mass movement events, especially in monsoon months.

The Setijhora landslide was triggered in June 2015 due to incessant rainfall. Temporal image from Google Earth (Figure 3) reveals the completion of the NHPC Tessta dam project IV in 2014. Along with the studied landslide, several mass movement events have initiated over the past few years as observed on the temporal Google earth imageries. As a consequence of the completion of the dam and blockage of the flow of Teesta River, the volume of the water stored upstream had raised the water level. Proximity to the reservoir may have contributed to the initiation of the landslide by increasing pore pressure, enhanced erosion (alteration) and toe cutting. An increase in the frequency of landslides has been reported by Singh et al. [16] in and around regions where hydropower projects have been constructed in Sikkim. The main boundary thrust (MBT) lies in proximity to this area. Geological Survey of India’s (GSI) map shows a major lineament through this section. A study [29] confirms thrust near the studied landslide. The moist tropical climate is experienced in the Himalayas up to an average altitude of 600 m. In Sikkim–Darjeeling region, most of the annual rainfall is received during May to October. The abundant rainfall results in frequent landslides that interrupt traffic and sometimes cause loss of human life. Apart from the altitudinal precipitation throughout the year in this region, the state also receives heavy monsoon precipitation [22].

Natural favourable conditions such as steep slope, presence of discontinuity and so on as well as unprecedented growth in anthropogenic activity amplify the problems related to different types of mass movement seen in this region [4,30–32]. These all factors have resulted in a complex slide at the reported study area. Various mass movements observed in this area are rockfall, topple and planar sliding. Different events of sliding and rockfall (Table 1) have been reported in this area. Most of the landslide events in the Himalayas occur in monsoon months, though sliding events viz. event 3 & 8 (Table 1) have occurred in the winter season as well. The reported landslide is still an active slide (Figure 1) causing problems to the traffic mainly in monsoon season. The importance of understanding the landslide event mechanism and causative factors is emphasized by the fact that this road is the sole link between the state of Sikkim, bordered by China, Nepal and Bhutan.

2.2. Geology of the study area

In the eastern part of the mystic Himalaya, the Sikkim–Darjeeling range of hills is a natural museum showcasing
different geological history and processes. Ranging from lesser Himalayan lower grade metamorphic rocks (phyllite) to the higher grade schist and gneiss (Figure 4), the hill ranges possess interesting geological information of the past. The Himalayan orogen is wedge shaped and characterized by a basal detachment and thrust fault that joins the detachment at depth [29].

The area of interest of this study is Setijhora, situated north of the Kalijhora town. In Teesta valley, the Main boundary thrust (MBT) is the thrust that transports older, Gondwana sandstones (Permian, Damuda subgroup) from the north over the younger, lower Siwalik sandstones (Miocene, Chunabati formation) to the south [33,34].

Mukul [29] has inferred that the MBT close to the study area is manifested as fault propagation synform–antiform pair, as a result of tectonic activity along a younger, south Kalijhora thrust (SKT) in its footwall that transported lower Siwalik rocks over middle Siwalik sandstones.

3. Methodology

In this study, the determination of geotechnical as well as geological parameters, viz. volumetric joint \( (J_v) \), rock quality designation (RQD), rock mass rating (RMR), slope mass rating (SMR) and continuous slope mass rating (CSMR) and geological strength index (GSI) along the lateral extent of the slide was carried out.

Orientations of discontinuities were analysed using the stereographic projection technique to assess the probable type of mass movement. The threshold of precipitation for the initiation of landslide in the study has been evaluated using statistical analyses methods.
considering temporal rainfall data and landslide inventory. Figure 5 shows the flowchart of the methodology followed in this study.

4. Results and discussion

4.1. Stability evaluation

In a regional context of landslide hazard evaluation study in Sikkim–Darjeeling Himalaya, earlier studies have relied on heuristic methods [4,26,35], deterministic physical models [26,36–41], statistical methods [30,42,43], etc. Statistical determination of thresholds of failure for physical parameters has been practiced in different parts of Sikkim and Darjeeling Himalaya [22,23,25]. Researchers have also done geomorphological hazard mapping [39] and analysis of landslide inventories [44]. Qualitative assessment of slope stability using stereographic projection technique and rock mass characterization systems has been studied in [45–49]. The problematic landslide in Setijhora was investigated (Figure 5) in detail for the characterization of the landslide using stereographic projection technique and qualitative evaluation using rock mass classification schemes including the RQD, RMR, CSMR and GSI.

4.2. Kinematic analyses

Joints, fractures, cleavages and deformation bands represent the discontinuities or the planes of weakness in rock masses. The presence of such discontinuities can profoundly reduce the bulk strength of the rock mass and can be detrimental to its stability.

The frequency, continuity and orientation of weak planes significantly affect the prediction of stability. Discontinuity analysis can be done by stereographic projection [50,51]. Stereographic analysis is used to determine potential failure types [52,53]. The stereographic projection is an important tool to visualize and compare the orientation of the rock slopes and the sets of discontinuities present and predict the type of probable failure. Plane failure occurs in situations where the strike of a set of discontinuities runs parallel to the slope and the discontinuities dip at an angle that is steep enough to produce sliding. Plane failure (Figure 6C) is not probable where the joint set has a strike, oblique to the rock type. Two intersecting sets of joints oblique to the slope lead to the wedge failure (Figure 6D), if the intersection lineation of the planes trends parallel to the direction of dip of the slope face, with a favorable amount of plunge.
The frictional resistance cone was plotted to assess kinematic and frictional conditions of the failure in the study area. In a frictional resistance cone for plane failure is plotted from the vertical, i.e., the centre of the stereo-net, if the poles to the planes lie within the cone then it is said to be stable and those poles to planes outside the cone are unstable. Poles inside the cone are stable because of their gentle dip and thus they do not exceed the critical slope angle needed to lose cohesion.

In the study area, six different locations (Figure 6A) with discontinuity orientations and slope face were recorded from SE to NW direction along NH-10. Measurements were taken using clinometer compass and rock logger software. Stereonet (11.3.0), software of Richard W. Allmendinger has been used for data plotting, calculation and interpretation. Kinematic analysis for the study area shows that the landslide is prone to plane and wedge failure (Figure 8). Intersection lineation plunging opposite to the direction of dip of the slope face created by discontinuities having a strike perpendicular to the slope results in topple prone wedges. Complex zone of fractures (Figure 1C) result from cross-cutting orientation of the discontinuities. The planes dipping very gently are considered as safe and frictional resistance cone for plane failure is plotted at 30° and counted from the vertical as the poles to the planes are
Figure 5. Flowchart of the methodology adopted for the assessment of landslide hazard in the present study.

Figure 6. (A) Locations along NH-10 where kinematic evaluation and rock/slope mass characterization has been done, representative diagram of failure modes (B) topple, (C) plane and (D) wedge along with the notations used for angular relation between discontinuity planes, lines and slope face of the studied landslide (after [54]).

Plotted, on the other hand, for wedge failure intersection lineation dipping more than 30° are considered as probable failure-prone wedges and the cone is plotted counting from the horizontal.

Location 1 (Figure 7A) at the southernmost part of the landslide consist of three sets of joints where joint J0 and J1 form probable wedge at intersection lineation 087/31. This location is prone to both wedge and plane failure. Pole to the joint plane one ([J1), pole 225/51] plot inside the daylight envelope for plane failure. Location 2 (Figure 7B) shows wedge at J0 and J1 intersection lineation 056.7/45.3. This part of the slide also has the threat of plane failure as pole to J1 (217/43) is inside the failure envelope. Four sets of joints were identified in location 3 (Figure 7C) and location 4 (Figure 7D). Though the wedges created due
to the joint surfaces’ intersection do not dip towards the slope, their near parallel strike with the slope raises another consequence. These wedges become topple prone if the slope face is poorly excavated and is highly weathered as in this landslide. This highly joined part of the landslide generated huge debris (Figure 1B) in the monsoon season. Location 5 and location 6 consist of highly jointed foliated rock but the discontinuity condition in these locations is comparatively favourable. Five different sets of joints were identified for the studied landslide (Figure 8A). Failure envelope for plane failure (Figure 8B) shows that two orientations of the joints from J1 daylight the plane failure condition. Intersection lineation of all joint sets (Figure 8C) shows that wedge failure is the most prominent failure mechanism prevailing in the study area. Intersection lineations formed by the joint sets J1, J3 and J4 are responsible for forming failure-prone wedges. None of the joint orientations daylight on the failure envelope for topplle failure (Figure 8D).
4.3. Rock mass characterization

Several rock mass characterization classifications have been used by earlier workers to quantify the quality of rock mass and it is essential for the empirical design approach in rock engineering [54]. Commonly used rock mass classification systems are rock mass rating (RMR) [55,56], slope mass rating (SMR) [57] for slope mass characterization, rock mass quality (Q) [58], Geological Strength Index (GSI) [59] and Rock mass strength (RMS) [60]. The role of the contribution of discontinuity orientation to failure is considered in more detail in the SMR system than in RMR.

In multilayer rocks, adjacent layers may develop different states of stress and therefore may develop different fracture patterns during uplift [61]. Thus, in the study area, which signifies a paleo ductile regime of depth (Figure 1C and D) different fracture distribution and density zones at its different parts during the exhumation period were observed. This study applies RMR [62], modified SMR [57] using the continuous function for correction, i.e. CSMR and GSI rock mass classification systems.

4.3.1. Rock mass rating (RMR)

The RMR system is widely used in slope stability analysis to determine the rock mass conditions. All the required RMR parameters were obtained on the field. The Schmidt rebound hammer was used to assess the UCS of the rock mass.

The basic RMR was estimated for six different locations (Figure 6A) along the slope from the southern to the northern end of the landslide. During monsoon and pre-monsoon seasons, field visit reveals the difference in slope conditions. The influence of precipitation has a direct bearing (Figure 9) on rock mass characteristics and stability conditions. In the dry season, the basic RMR ranges from 35 to 59 and in the monsoon season it ranges from 23 to 51 (Table 2).

RMR values are 10–29 in the dry season and in monsoon some the location shows RMR in negative characterizing inferior and unstable rock mass. Locations 2 and 3 give the lowest value of RMR. All the rock masses come under class IV and class V of [62] RMR classification characterizing all locations as poor and very poor rock mass quality with very less stand-up time.
4.3.2. Continuous slope mass rating (CSMR)

The values of CSMR are listed in Table 3. A total of eight possible failures are found, out of which seven scenarios show unstable to completely unstable stability grade with more than 0.6 probability of failure.

Location 1 plane failure, location 2 wedge and plane failure, location 3 failure scenarios show precarious conditions. Location 5 failure scenario shows partially stable conditions for the slope and joint orientations. In locations 1, 2 and 3, the CSMR values come within the lowest class, i.e. grade V with a failure probability of 0.9 according to [57]. The probable mode of failure at different locations of the slide is shown in Table 4.

4.3.3. Geological strength index (GSI)

Geological Strength Index (GSI) is widely used in geotechnical engineering because it can be determined easily in the field based on visual observation. The GSI has been calculated according to the modified quantitative GSI system proposed by [50,63], for six locations along the slope (Table 5).

Two factors are considered for the index, first one is structure rating (SR) and another is surface condition rating (SCR) (refer appendices for equations). The SR and SCR values are plotted in the graph (Figure 10) to obtain the GSI.

A correlation has been derived from the linear fitting of RMRb vs. GSI for the studied location (Figure 11). The equation derived empirical relation is

\[ RMRb = 1.9376 \times (GSI) - 29.2 \]

This empirical equation can characterize rock mass in similar areas in the Himalayas where highly sheared and jointed phyllitic and quartzite rocks are common.

4.4. Rainfall threshold

Rainfall is one of the most important triggering factors that contribute to the initiation of landslides. Sometimes a heavy rainfall spell of 1 or 2 h can cause mass movement, or sometimes it can be an antecedent rainfall over the past few days. Rainfall and continuous

Table 2. Rock mass rating of all the parameters for different locations of the study area.

| Location | UCS (A) | RQD (B) | Joint spacing rating (C) | Joint condition rating (D) | Groundwater rating (E) | Dry season (D) | Monsoon season (M) | Adjustment factor for joint orientations (F) | RMRb (A + B + C + D + E) | RMR (RMRb + F) |
|----------|---------|---------|---------------------------|---------------------------|------------------------|----------------|-------------------|---------------------------------------------|---------------------------|----------------|
| 1        | 54      | 36      | 10                        | 10                        | 15, 7                  | 50             | 41                | -10                                        | 40                        | 31             |
| 2        | 56      | 78      | 10                        | 10                        | 15, 7                  | 59             | 51                | -25                                        | 34                        | 26             |
| 3        | 21      | 70      | 8                         | 0                         | 15, 0                  | 38             | 23                | -25                                        | 13                        | -2             |
| 4        | 25      | 48      | 10                        | 0                         | 15, 4                  | 35             | 24                | -25                                        | 10                        | -1             |
| 5        | 49      | 98      | 10                        | 10                        | 15, 7                  | 59             | 51                | -10                                        | 49                        | 39             |
| 6        | 25      | 44      | 8                         | 10                        | 15, 4                  | 43             | 32                | -10                                        | 33                        | 22             |

Table 3. Slope mass rating for different slope mass using continuous functions.

| Location | Wedge (W) | Plane (P) | CSMMR |
|----------|-----------|-----------|-------|
| 1        | 0.51      | 0.63      | 1.15  |
| 2        | 0.6       | 0.91      | 1.15  |
buildup of pore pressure lead to the failure of critical slopes. The minimum quantity of rainfall required to initiate the landslide determines the area’s rainfall threshold [64]. Some authors have proposed the threshold as the lower limit below which landslides do not occur [18, 23, 32]. Some researchers have defined threshold as the upper limit, which when exceeded will always result in landslides and the threshold is the limit that separates non-triggering and triggering rainfall events [65]. Various rainfall threshold determination methods have been used by researchers, viz. rainfall intensity (I) and duration (D) thresholds, threshold based on the total event rainfall (R) [20, 22], rainfall event (E)–duration (D) thresholds and rainfall event (E)–intensity (I) thresholds.

In this study, the rainfall event duration based threshold of antecedent rainfall for 3, 5, 7, 10, 15, 20 and 30 days is determined using the methodology for establishing rainfall threshold in the eastern Himalayas as proposed in [21]. Bhandari et al. [21] have proposed the following threshold for the eastern Himalayas based on normalized cumulative event rainfall ($E_{MAP}$).

- $E_{MAP} < 0.05$ for low probability of landslides,
- $0.05 < E_{MAP} < 0.10$ for intermediate probability of landslide,
0.10 < $E_{\text{MAP}} < 0.20$ for high probability of landslide $E_{\text{MAP}} > 0.20$ when landslides will always occur.

The $E_{\text{MAP}}$ is the normalized cumulative event rainfall (a unitless parameter), estimated by dividing cumulative event rainfall ($E$) by mean annual precipitation of the area. (MAP) ($E_{\text{MAP}} = E / \text{MAP}$). It is a long-term yearly average precipitation obtained from historical rainfall records.

Daily rainfall data from https://power.arc.nasa.gov/data-access-viewer/ has been taken for the duration of 1990 January 1st to 2019 December 31st. The long-term mean annual precipitation (MAP) is calculated from this 30-year data. The MAP for the study is found to be 1113.97 mm. GSI database on landslide inventory, ancillary data from news articles and blogs, social media reports has been used to prepare landslide inventory database for the study area. As the reported point-specific landslide was triggered in June 2015, the daily rainfall data from 2015 to 2019 is used for the determination of rainfall threshold. The cumulative rainfalls for 2015 to 2019 (Figure 12) are 1380.53, 1718.52, 1570.99, 1536.23 and 1712.68 mm respectively. The monsoonal precipitation is 1072.60, 1273.45, 1159.98, 1172.19 and 1324.03 mm respectively from 2015 to 2019. The monsoon precipitation accounts for 77.7%, 74.1%, 73.87%, 76.3% and 77.3% of the total rainfall each year respectively.

The daily average rainfall over these years in the monsoon months of June to September is 9.83 mm/day. The yearly daily average rainfall is 4.33 mm/day. Six events (Table 1) have been considered to evaluate the rainfall threshold of the landslide. 3, 5, 7, 10, 15, 20 and 30-day cumulative rainfall (Table 6) is calculated to reveal its effect on the initiation of slide. The $E_{\text{map}}$ when exceeding 0.10 there is a high probability of slide and when it exceeds 0.20 then a slide always occurs. For the study area, a cumulative rainfall of 111.39 mm is equal to $E_{\text{map}}$ of 0.10 and 223 mm of rainfall accounts for $E_{\text{map}}$ 0.20. Considering cumulative rainfall over 3 days prior to failure shows that (Figure 13A) 83.33% of events come under low probability of occurrence. Cumulative rainfall prior to failure over 5, 7, 10, 15, 20 and 30 day (Figure 13B–F) show an increasing effect on initiation of landslide with 16.67%, 16.67%, 50%, 66.67%, 100% and 100% probability of occurrence respectively. The results show a greater contribution of cumulative rainfall over a period than the rainfall on the day of failure.

Cumulative antecedent rainfall of 111.3 mm over 20 days and 223 mm in 30 days has resulted in a higher probability of occurrence of landslides. The consideration of intensity of a single day rainfall that can contribute highly towards initiation of slide can be inferred 12th August 2017. The amount of rainfall on the day of slide is 54.82 mm with an intensity of 2.28 mm/h. Thus a rainfall intensity of more than 2 mm/h for more than 55 h can greatly increase the probability of initiation of a slide. This influences the $E_{\text{map}}$ as it becomes more than 0.10 over a concise span of days. The intensity of rainfall accounting for higher amounts of precipitation in the short term having less effect on the initiation can be correlated with the fact that a longer period of precipitation leads to build-up of pore pressure over time and ultimately leads to failure. Dikshit and Satyam [22] had evaluated the rainfall thresholds for landslide
Table 6. Antecedent cumulative rainfall before failure events for different spans of time and calculated corresponding $E_{\text{map}}$ values.

| Date       | Cumulative rainfall event, $E$ | $E_{\text{map}}$ |
|------------|--------------------------------|------------------|
|            | Days                          | 30   | 20  | 15  | 10  | 7   | 5   | 3   |
| 27/6/2015  | 230.83                        | 169.54| 115.38| 89.86| 61.73| 56.76| 40.75| 0.21| 0.15| 0.11| 0.08| 0.05| 0.05| 0.03|
| 9/7/2016   | 307.69                        | 254.78| 178.78| 122.17| 82.55| 52.3 | 24.93| 0.27| 0.22| 0.16| 0.10| 0.07| 0.04| 0.02|
| 21/8/2016  | 283.17                        | 112.73| 93.65 | 57.08 | 47.07| 24.43| 12.35| 0.25| 0.10| 0.08| 0.05| 0.04| 0.02| 0.01|
| 12/8/2017  | 391.26                        | 309.79| 278.9 | 221.18| 178.06| 150.63| 130.61| 0.35| 0.27| 0.25| 0.19| 0.15| 0.13| 0.11|
| 15/9/2018  | 367.95                        | 225.29| 189.85| 141.98| 107.82| 59.6 | 32.84| 0.33| 0.20| 0.17| 0.12| 0.09 | 0.05| 0.11|
| 3/7/2019   | 205.59                        | 149.85| 93.05 | 80.08 | 26.62| 14.2 | 10.68| 0.18| 0.13| 0.08| 0.07| 0.02 | 0.01| 0.009|

Figure 13. Relationship between antecedent rainfall prior to failure (3, 7, 10, 15, 20 and 30 days) and daily rainfall for the reported events plotted with $E_{\text{map}}$ 0.10, i.e. 111 mm, above which there is a high probability of landslide occurrence for the study area.

occurrence for the nearby town of Kalimpong, in West Bengal. They estimated that an antecedent rainfall of 133.5 mm over 20 days leads to landslide occurrence. The less amount of rainfall needed to initiate slide in the Setijhora than Kalimpong can be satisfied by the fact of already prevailing phyllite and highly jointed quartzite rock masses.

5. Conclusion

This study demonstrates the following conclusion points:

1. The kinematic evaluation and rock mass characterization classifications seem to be very important tools for the assessment of point-specific landslides on a large scale, as it helped in determining the landslide vulnerability. It will further aid in the identification of unstable slopes and provide scientific knowledge related with causes and possible consequences as well as standardizing the approach for hazard assessment.

2. Onsite Rock mass classification and assessment of the stability grade of the rock mass, employing RMR, CSMR and GSI classification methods provide important insights into existing stability grades of road cut slopes in the highly precarious Himalayan terrain. In the present study, these methods have significantly helped in identifying sites that are highly vulnerable to landslide owing to weak and deformed rocks.

3. High rainfall is the major factor for triggering landslides, as during monsoon season rock masses stability grade ranges from partially stable to
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