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Slope Stability and Damming Probability Assessment of a Recurrent Landslide in Garhwal Himalayas

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Abstract

Landslides are one of the most frequently occurring geological hazards in the mountainous areas, accounting for substantial environmental and economic damages. Considering the severity of landslides and their possible consequences, the present study investigates a recurrent landslide located at Bhatwari, Uttarakhand. Stability grade and associated risks of the studied landslide slope were determined using geospatial and geotechnical approaches. For stability assessment, rock mass classification and numerical methods have been employed. Factor of Safety (FoS) values are determined for static and pseudo-static loading conditions. Some of these analyses also incorporate the effect of pore water pressure. Further, different geomorphic indices, such asthe Morphological Obstruction Index (MOI), Hydro-morphological Dam Stability Index (HDSI)and Dimensionless Blockage Index (DBI) were used for checking landslide dam development potentiality in the Bhagirathi River. The results suggest that the slope is critical for simulated scenarios and indicate that slope forming materials may fail due to triggering factor like an extreme rainfall and/or earthquake events. However, the landslide damming probability assessment reveals that dam formation has negligible possibility and even if it develops, then it may not sustain for a longer time. Reactivation of the slide will definitely damage the NH-108, thus the slope needs immediate attention for implementation of suitable stabilization measures.

Keywords: Garhwal Himalayas; Landslide; Slope stability; Finite element method, Landslide damming; Risk assessment.

1 Introduction

In higher reaches of the Indian Himalayas, landslides are the most perilous natural disaster that not only affect infrastructures but also cause enormous impact on human lives. In recent times, the number of fatal landslides in the hilly terrain have increased due to infrastructural activity growth, further, unplanned urbanization accelerates the rate of movement. Following the definition of Cruden and Varnes 1996 [1], landslides can be categorized based on the type of movements, the material involved, volume, and velocity. Although, in general, they are defined as the downslope movement of the earth's materials under the influence of gravity. There can be different combinations of factors that may cause slope instability in a region. Apart from geological and topographical conditions, one of the main causes of risks in the Himalayas are the harsh climatic events such as cloud bursts and the subsequent flash floods which may lead to landslides, and floods in the Himalayan region [2].

In Garhwal Himalayas, a number of landslides are aggravated during monsoon season. Slides related with heavy rainfalls are pernicious, causing countless casualties in many parts of the world. In June 2013, Uttarakhand experienced massive flash flood (Kedarnath tragedy) leaving thousands of people dead and caused massive damage to existing infrastructures nearby river channel [3]. The rise and fall in river water level during monsoons is quite prominent. Considering the recent events, it is evident that the threat of landslides is expanded in downhill areas by means of landslide dam breach- ing and valley blocking. Landslide dam forms when a watercourse is obstructed natu- rally due to slope failure. This phenomenon has devastating effect on environment as they may prompt dam-break flooding distressing large areas in the downstream region [4] and a barrier lake outburst in the upstream [5]. Generally, for landslide dam formation the following factors are often crucial: (i) high relief with narrow valley; (ii) the deposition thickness of landslide debris mass; (iii) confluence of tributaries; (iv) wide valley left behind the dam [6]. According to their relationship with the valley floor landslide dams can be categorized geomorphically into six types [7] such as **Type I:** in comparison to the width of the valley floor, dams are modest and do not span the entire valley; **Type II:** larger dams that cover the entire valley floor, occasionally dumping material on the opposite valley sides that are high above; **Type III:** dams cover the valley on both sides and extend a long way up- and down-valley from the failure (usually, the biggest amount of landslide debris is involved in these dams); **Type IV:** material from both sides of a valley simultaneously failing causes landslide dams to form. In the valley's center, the landslides can be next to one another or placed in opposition to one another; **Type V:** landslide dams are created when a single landslide splits into many debris lobes that spread across the valley floor and create two or more dams in the same river reach; **Type VI:** landslide dams consist of one or more failure surfaces that pass beneath a stream or river valley and appear on the opposite valley side from the landslide [8]. The likelihood of landslides blocking the valley and the stability of the ensuing dams have both been measured using a variety of geomorphometric indicators [9].

The present work utilizes the rock mass characterization using Geological Strength Index (GSI) & Rock Mass Rating (RMR_b) and slope stability analysis using finite element method (FEM) of a rock slide overlain with a debris in the Bhatwari region of Uttarkashi district, Uttarakhand. Extensive damage to the houses and businesses was caused due to rainfall-induced landslides in August 2010 in Bhatwari and this zone along NH-108 is still showing subsidence [10]. It necessitates to analyze the slide in the area with scrutiny by means of a quantitative approach to determine the stability ofthe slope and the landslide damming probability. This work aims to understand the probable landslide damming process using slope failure mechanism, dam dimension, and dam stability evaluation.

2 Study area

The studied slope is a rock-cum-debris slide. It is located at longitude 30°48'44"N and latitude 78°37'12"E in the Bhatwari township of Uttarkashi district at a distance of about 600 meter downstream from Bhatwari village. Bhagirathi River flows alongside the National Highway (NH-108), connecting Dharasu to Gangotri, where the investigated slope is situated. The area is near the MCT (Main Central Thrust), thrust which demarcates a transition from the higher-grade metamorphic rocks of Greater Himalayas in the North to the lower-grade metamorphic rocks of the Lesser Himalayas. Thus, the study area is highly weathered and fractured due to the presence of thrust zone. It is a part of the Munsiari formation of the Higher Himalayas that comprises predominantly of gneissic and metabasic rocks [11]. The slope is composed primarily of gneiss and is overlain by debris material. Since 2009, subsidence in the region has been observed. Between 12–13th of August, 2010, the area witnessed a landslide triggered by rainfall, and the Uttarakhand floods of 2013 brought another landslide on 16th of June, 2013 [12], which was initially intensified due to 2012 Asi Ganga flash flood [13]. The average annual rainfall received in the region is nearly 1400 mm (2011-2019). Seismically, the area lies in Zone IV of earthquake zonation map of India [14]. This is an intricate landslide and the main causative factors include the erosion of the toe of slope by Bhagirathi, highly jointed gneiss with existence of mica schist foliations, saturated overburden, continuous and high intensity rainfall [15]. The location of the study area is shown in Fig.1.

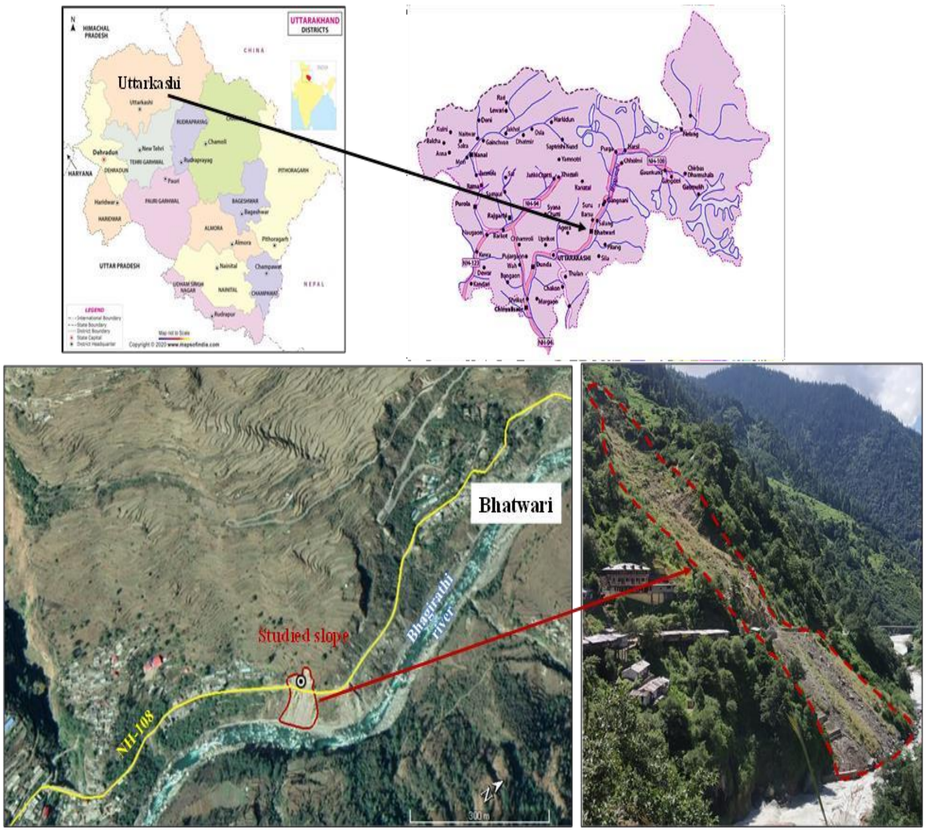

Fig.1. Location map of the study area

3 Methodology

The present work focuses on the empirical rock mass classification techniques and numerical methods of slope stabilization to calculate Factor of Safety (FoS) value, followed by the probability analysis of landslide dam formation. A detailed geological field survey was carried out in order to determine the condition of exposed rock mass, type of debris material, overburden thickness, condition and attributes slope and discontinuities. Rock samples of intact rock were collected for laboratory analysis to ascertain certain geotechnical properties.

3.1 Rock mass classification system

Rock Mass Classification System are utilized in a variety of engineering design and stability analysis processes. They are centered on empirical relationships between parameters related to rock mass and provide a qualitative assessment of rock mass conditions.

Geological Strength Index (GSI)

Hoek and Brown, 1997 [16] proposed the GSI approach for rock mass categorization which principally describes the blockiness of rock mass and the surface conditions of discontinuities. Further it was modified by [17], providing a quantitative numerical foundation. The same methodology was employed in the present investigation to assess the GSI values of rock slopes. This modified quantitative rock mass classification is based on the structure rating (SR) and surface condition rating (SCR). Volumetric joint count (*Jv)* is the foundation of SR whereas SCR is based on roughness, weathering, and joint infilling. The correlations are as follows:

$$SR = -17.5 \ln (Jv) + 79.8 \quad (1)$$

where, $Jv = 1/S1 + 1/S2 + 1/S3 + \cdots + 1/Sn$ (2)

($S1$, $S2$, $S3$ ... Sn are the average spacing of the joint sets)

$$SCR = Rr + Rw + Ri \quad (3)$$

Rock Mass Rating (RMR$_b$)

The Bieniawski's (1979) [18] Rock Mass Rating (RMR) approach is based on an analysis of five discontinuity parameters: (i) Uniaxial Compressive Strength (UCS) of rock mass, (ii) Rock Quality Designation (RQD), (iii) spacing of discontinuities, (iv) condition of discontinuities and (v) groundwater condition. Bieniawski (1989) [19] provided rating values for these five criteria, and by algebraically adding these rating values, one gets the RMR$_{basic}$, which is then used to categorized the rock mass into five quality classes ranging from very good (Class I: 80-100) to very poor (Class V: <20). Rock Quality Designation (RQD) value was estimated from its empirical relationship with the volumetric joint count (Jv) as given by [20],

$$RQD = 110 - 2.5Jv \quad (4)$$

where Jv is obtained from equation (2)

3.2 Numerical Simulation

Numerical simulation is a reliable method for visualizing and solving challenging geo-engineering problems [21]. It is a powerful method for slope stability analysis because it has the ability to take into account slope geometry, material properties and different constitutive simulations in slope models to calculate the Factor of Safety (FoS) of slope [22].

Finite Element Method (FEM)

Finite Element Method (FEM) is a widely used continuum numerical method. In this study, a 2D deterministic FEM program is executed using RS2 11.0 to determine the factor of safety of slopes. In FEM, the numerical model is divided into multiple zones known as meshed elements and boundary conditions are applied. The Shear Strength Reduction (SSR) technique in association with material attributes are used to estimate the factor of safety and likely failure mechanism [23]. Stability by shear strength reduction is a method that the factor of safety is determined by weakening the soil or rock in stages in an elastic-plastic finite element analysis until the slope fails. The factor of safety is considered to be the factor by which the soil or rock strength needs to be reduced to reach failure [24] [25]. The analyses have been carried out for static, pseudo-static and wet conditions using the Generalized Hoek and Brown (GHB) criterion for the gneissic rock mass and the properties of overlying debris material were assigned using Mohr-Coloumb criterion. The GHB constants (m_b, s and a) were calculated from RocData of Rocscience which uses GSI as an input parameter.

3.3 Landslide Damming Probability

In literature, limited methods are available in support of the assessment of landslide damming potentially. However, recently Stefanelli et al., 2016 [9] proposed geomorphic index based methods for quantitative assessment of the landslide dams. The proposed method also incorporates the dam stability index-based assessment i.e., if the dam is formed then whether it will get stable and block the upstream area or form but may be collapsed over time. In this study, the methodology of [9] was applied to the present slope. Fig. 2 shows the flow chart of the adopted methodology.

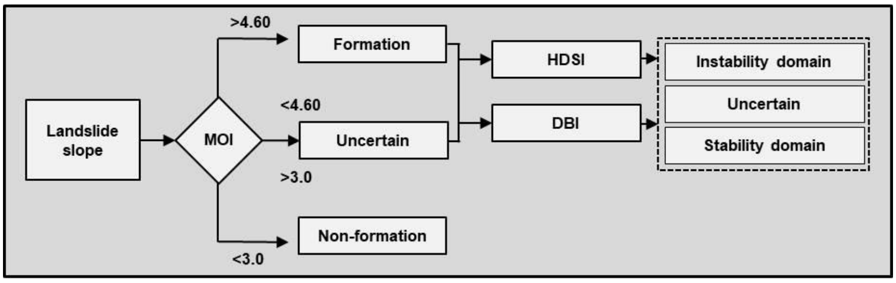

Fig. 2 Methodological diagram for landslide damming assessment (modified after Stefanelli et al., 2016)

Morphological Obstruction Index (MOI)

The morphological obstruction index (MOI) shows the relation between the landslide damming volume and the river width. It is generally observed that the formation of a landslide damming event depends on the displaced landslide material volume and width of the river and the dam is formed when the volume of the landslide is greater than the river channel width at the blockage point. Based on this relation MOI is defined as:

$$MOI = \log(V_I/W_V) \quad (5)$$

where, V_I represents the landslide volume (m^3) and W_V represents the width of the dammed valley (m). The resultant index is categorized into three domains, e.g. (i) Non-formation domain: MOI<3.00, lower than this value is not support for dam formation; (ii) Uncertain domain: 3.00<MOI<4.60, the behavior of the dam is uncertain and it's hard to infer any stability state of the dam and (iii) Formation domain: MOI>4.60, indicates the displaced materials can block the river course and form a dam.

Hydro-morphological Dam Stability Index (HDSI)

Hydro-morphological Dam Stability Index (HDSI) is used to gauge the stability domain of a formed landslide dam. In this index, the upstream catchment area from the blockage point and the river channel gradient is used as a proxy for explaining the destabilizing action of the river in the blocked section. Usually, if the catchment area is large enough and the channel gradient is relatively high, then the formed dam may be subjected to intense fluvial undercutting and as a result, it will get punctured. So, the condition reveals an instability domain. Similarly, if the catchment area and channel gradient are lower than the threshold then the channel may get blocked and categorized as a stable domain. Based on this HDSI is defined as:

$$\text{HDSI} = \log\left(V_1/(A_b \times S)\right) \quad (6)$$

where, V_1 is the landslide volume (m^3), A_b is the upstream catchment area (km^2) from the blockage point and S is the longitudinal local river slope gradient (m/m). Three domains are used in the interpretation of HDSI e.g. (i) Instability domain: HDSI<5.74, which indicates the formed is unable to block the river; (ii) Uncertain domain: 5.74<HDSI<7.44, in this the estimation of the stability of the blockage condition is uncertain and (iii) Stability domain: HDSI>7.44, in this condition it's assumed that the landslide will block the river and the condition remain stable.

Dimensionless Blockage Index (DBI)

Dimensionless Blockage Index (DBI) is another type of measure used to define the stability domain of a landslide dam. The index considers the dam height and upstream catchment area with landslide volume to infer the dam stability. DBI is defined as:

$$\text{DBI} = \log\left((A_b \times H_d)/V_1\right) \quad (7)$$

where, A_b is the upstream catchment area (km^2), H_d is the dam height (m) at the blockage point and V_1 is the landslide volume (m^3). Here, three sections are used to explain the dam stability condition e.g. (i) Instability domain: DBI>3.98, the dam may be formed but the situation remains unstable; (ii) Uncertain domain: 2.43<DBI<3.98, the formed dam may stable or unstable and (iii) Stability domain: DBI<2.43, indicates the developed dam remains stable and block the channel.

4 Results and Discussion

This study uses several methodologies to conduct stability analysis of the rock slope after a thorough review of the geological and geotechnical data. The empirical approach was used to determine the quality and grade of slope. GSI and RMR were calculated and shown in the Table 1. The FEM based Numerical modelling technique for three cases, gravity loading condition (static), gravity loading condition (static) with the effect of pore pressure and seismic loading condition (pseudo-static) for the slope were used. The horizontal (α_h) and vertical component (α_v) for seismic loading were calculated for Zone IV. The deformation and displacements of the computed slopes are represented in the Fig. 3. FoS values of the slope are listed in the Table 2.

Table 1. Determination of rock mass quality from rock mass classification system

Rock Mass Rating Technique	Value	Class
Geological Strength Index (GSI)	30	Blocky Disturbed
Rock Mass Rating (RMR_b)	53	Class III (Fair)

Table 2. Factor of safety (FoS) values of the studied slope

Condition	FoS
Dry-static condition	1.02
Wet-static condition	0.98
Pseudostatic condition	0.84

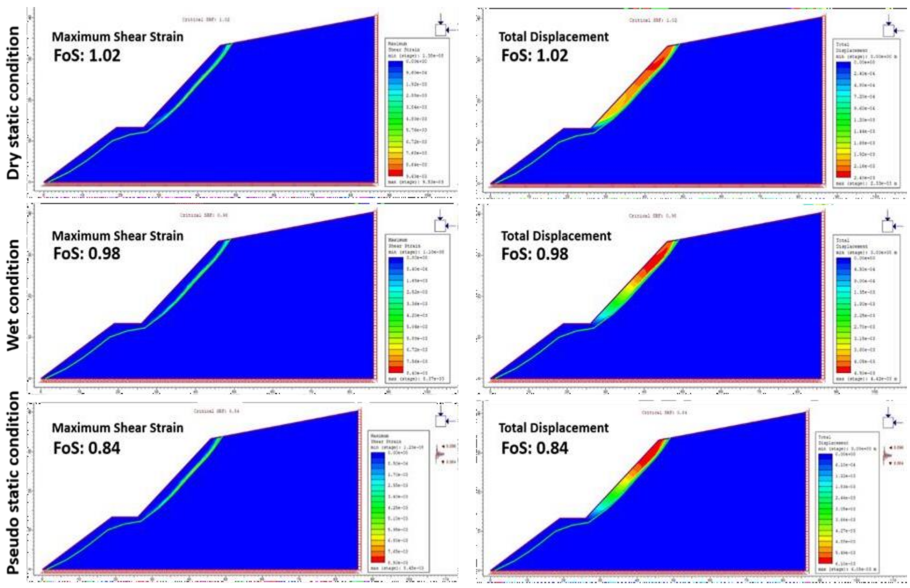

Fig.3. Stability analysis of the studied slope

The result of the stability assessment reveals that studied slope is highly vulnerable to failure and it has a tendency to block the river. For this purpose, we studied the landslide damming potentially of the considered slope. Based on the above indexes first, we derived the MOI to check whether the studied slope has the potential to block the channel or not. For this, we obtained the landslide volume (V_l) and width of the valley (W_V). Here, the method suggested by [1], is used for landslide volume estimation. The mathematical expression of the formula is Volume = ($\pi \times L_d \times D_d \times W_d/6$), where, L_d is the length of the landslide from crown to toe, D_d is the depth of the displaced mass and W_d is the width or say length between the landslide flanks. In order to derive these values, field measurements as well as high-resolution Google Earth images (L_d = 120 m, D_d = 4 m, and W_d = 65 m) were considered and based on that the estimated volume is approximately 16328 m^3 for the considered landslide. Thereafter, the average river valley width, which is ~30 m at the landslide section is considered. Using this information, the MOI was calculated and the derived value was 2.74. The obtained value indicates a boundary condition between non-formation to an uncertain domain (Fig. 4). Given the lack of a complete understanding of landslide processes and the factors controlling their magnitude (size/volume), the stability status was analyzed to ensure if the dam forms, whether or not it will be stable. For this purpose, the upstream catchment area, river channel gradient and probable dam height information were obtained as about 3484 km^2, 0.005 m/m and 21 m, respectively. Thereby, the derived HDSI and DBI are found to be about 5.45 and 3.65, respectively for the present slope. The overall interpretation of both the indexes indicates even if the dam is formed, it may not sustain at this particular section due to the intense fluvial action.

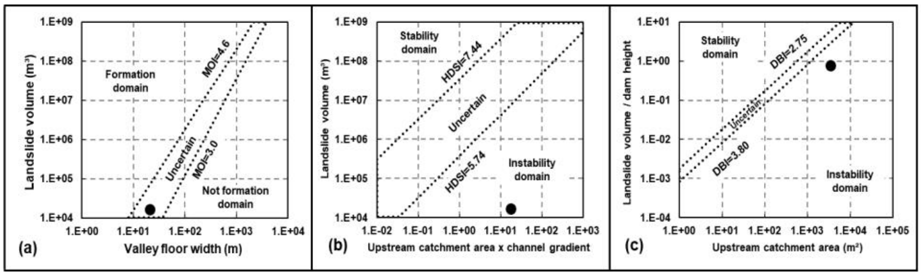

Fig.4. Landslide damming assessment of the Bhatwari slide: a. Morphological Obstruction Index (MOI), b. Hydromorphological Dam Stability Index (HDSI) and c. Dimensionless Blockage Index (DBI). The black circle indicates domain position of the present landslide in three indexes.

5 Conclusion

An attempt has been made to study the stability grade of the slope through numerical modelling techniques. The analysis has been done by Finite Element Method (FEM) coupled with SSR method to obtain factor of safety (FoS) value. It can be concluded that slope is critical for simulated conditions and shows that triggering factors like extremely heavy rain and/or earthquake events may cause slope-forming materials to fail. The attempt to assess the probability of landslide damming shows that chances of a dam formation is quite low, and even if it happens, it might not last for an extended period of time. Reactivation of the slide will definitely damage the NH-108, thus the slope needs immediate attention for implementation of suitable stabilization measures.

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