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A Review on Analysis and Mitigation Strategies for Landslide Risk Management: Case studies of Nainital, Satluj Valley, Pipalkoti, Jhakri, Panjpiri in Himalayan Region, India

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Abstract

Landslides affecting life and property losses has become a serious threat in various countries worldwide which highlights the importance of slope stability and mitigation. The methods and tools employed for slope stability analysis, ranging from traditional limit equilibrium methods to worldly-wise numerical modelling techniques. It focuses on the importance of accurate and reliable data collection, including geotechnical investigations, in developing precise slope stability assessments. Further, it also addresses challenges associated with predicting and mitigating slope failures, particularly in dynamic and complex environments. Mitigation strategies for unstable slopes were systematically reviewed of different researchers, encompassing both traditional and innovative measures. Traditional methods, such as retaining walls and drainage systems, the mitigation strategies were explored, emphasizing both preventive measures and remedial interventions. These include the implementation of engineering solutions such as slope structures, and Matrix Laboratory (MATLAB) techniques along with the comprehensive analysis of four prominent slope stability assessment tools: Rock Mass Rating (RMR), Slope Mass Rating (SMR), and the Limit Equilibrium Method (LEM). The comparative analysis of these tools highlights their respective strengths, limitations, and areas of application, providing researchers, authors, and practitioners with valuable insights to make informed choices based on project-specific requirements. To ensure the safety and sustainability of civil infrastructure, a thorough understanding of geological, geotechnical, and environmental factors in combination with cutting-edge technologies is required. Furthermore, it highlights the important role that slope stability assessment and mitigation play a major role in civil engineering for infrastructure development and mitigation strategies.

1. Introduction

Slope stability is a crucial aspect of civil engineering that requires careful attention due to its significant implications for the safety and functionality of infrastructure [1]. The significance of slope stability assessment and mitigation arises from the potential consequences of slope failure, ranging from property damage to loss of life. In the context of civil engineering, a slope can be defined as an inclined surface of the earth's crust, and its stability depends on a delicate balance of geological, geotechnical, hydrological, and environmental factors. As populations grow and urbanization step up [2], The importance of conducting a thorough analysis of slope stability and implementing effective measures to prevent landslides becomes more and more crucial over time [3]. Civil infrastructure, including roads, bridges, and buildings, often encounters challenging terrain, requiring engineers to navigate and build upon slopes. However, the inherent

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complexities of slopes, influenced by natural forces and human activities, create vulnerabilities that necessitate thorough examination. Geological characteristics, such as the type of rock and structural features, significantly influence the stability of a slope [4]. For instance, slopes composed of loosely consolidated soils or weathered rock may exhibit greater susceptibility to instability.

Geotechnical factors, such as soil composition, shear strength, and pore water pressure, play a crucial role in slope stability assessment. Understanding the mechanical behaviour of soils under different conditions is crucial for predicting potential failure modes and designing appropriate mitigation measures [5]. Furthermore, the correlation between hydrological factors and slope stability cannot be overstated. Rainfall patterns, groundwater flow, and surface water runoff can trigger changes in pore water pressure [6], impacting the overall stability of slopes. Identification of unstable slopes is a multifaceted process that involves a combination of field surveys, geotechnical investigations, and cutting-edge monitoring technologies. Modern techniques, including satellite imagery, Light Detection and Ranging (LiDAR), and remote sensing, provide engineers with invaluable data for assessing slope conditions and identifying potential hazards [7]. The integration of Geographic Information Systems (GIS) facilitates a comprehensive understanding of the spatial relationships between geological and hydrological features. Once an unstable slope is identified, the subsequent challenge lies in effective mitigation strategies to reduce the risk of slope failure.

Mitigation measures range from structural interventions, such as the construction of retaining walls and slope stabilization structures, to non-structural approaches like land-use planning and vegetation management [8]. The rapidly developing area of civil engineering makes use of cutting-edge technology, such as geotechnical instrumentation and numerical modelling, to improve the accuracy of slope stability evaluations and the planning of mitigation strategies. The assessment and mitigation of slope stability in civil engineering is crucial for developing resilient infrastructure that can withstand natural and human-made challenges [9]. This introduction lays the groundwork for an in-depth exploration of the factors that impact slope stability, the methods used to assess it, and the various mitigation strategies that engineers use to ensure the safety and sustainability of civil infrastructure in areas prone to slope-related hazards.

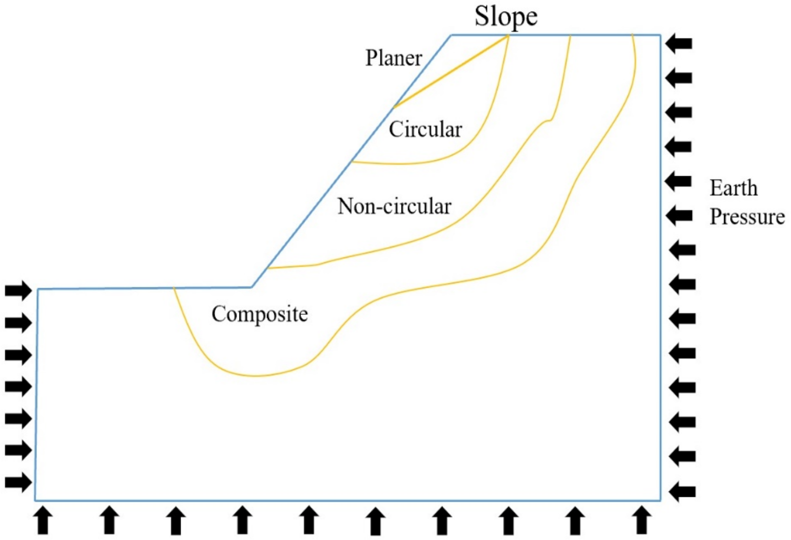

Figure 1. Predicted slope failure surface [9]

1.1. Background

Unstable slopes are a major problem in geotechnical engineering, posing a significant risk to people's lives, infrastructure, and the environment. Given the natural tendency of slopes to become unstable, it is vital to have a thorough understanding of the various factors that contribute to this issue [10]. This understanding is not only critical for risk management but also forms the base for the formulation and implementation of effective mitigation strategies [11]. The topographical complexity of hilly and mountainous regions, coupled with a dynamic interplay of geological, environmental, and anthropogenic factors, underscores the urgency of addressing slope instability. Natural processes, such as weathering, erosion, and seismic activities, interact with human-induced alterations, such as construction and mining, creating a delicate balance that, when disrupted, can result in catastrophic slope failures [12]. In densely populated areas, the consequences of unstable slopes extend beyond immediate safety concerns. Infrastructure development, urbanization, and economic activities often overstep upon vulnerable terrains, heightening the potential for disasters [13].

Additionally, the environmental impact of slope instability, including soil erosion and sedimentation in water bodies, further underscores the need for a proactive and systematic approach to mitigate these risks. Recognizing the gravity of the situation, researchers, engineers, and policymakers have intensified efforts to explain the complexity of slope instability [14]. This involves a multidisciplinary approach that combines geological, geotechnical, and environmental sciences with cutting-edge technologies and engineering principles. By analytic contributing factors and their interdependencies, professionals can develop targeted strategies to assess, manage, and mitigate slope instability [15]. In essence, the background of slope stability assessment and mitigation is characterized by the imperative to safeguard both human well-being and the integrity of the natural environment. The ongoing pursuit of knowledge and innovative solutions in this field reflects a commitment to sustainable development and resilience in the face of the inherent challenges posed by unstable slopes [16].

1.2. Slope Stability

Slope stability is the capacity of a slope or embankment to resist and maintain balance against external forces and pressures. This critical geotechnical engineering component involves evaluating the slope geometry, material characteristics, water conditions, and external loads, among other aspects that affect slope stability [17]. The stability of a slope is largely dependent on its geometry, which includes elements like height and angle. Stability is also influenced by material characteristics such as strength, cohesiveness, internal friction, and kind of rock or soil [18]. Conditions related to water, including groundwater or rainfall-induced pore water pressure, can weaken soil and increase the risk of landslides, especially when saturation sets in. External loads that are introduced by constructions or changes in land usage can also impact a slope’s stability. Slope failures can take many other forms, including slides, flows, falls, and creep, which serve as more examples of the various ways in which slopes can become unstable. Comprehending these variables and failure modes is crucial to carrying out exhaustive evaluations of slope stability and putting into practice efficient corrective actions [19].

The ability of a system, structure, or item to sustain a balanced and unchanging condition throughout time in the face of external effects or disturbances is generally referred to as stability [20]. Stability in geotechnical engineering typically refers to the ability of man-made or natural slopes, embankments, or structures to withstand certain failure causes. Analysing the forces operating on a slope and determining whether it is likely to fail or remain stable are key components of slope stability [21]. The geometry of the slope, the characteristics of the materials that make up the slope (such as rock or soil), the presence of water and how it affects the strength of the soil [13], and outside loads or forces are some of the factors that affect stability. An unstable slope may suffer movements or failures that have potentially dangerous outcomes, whereas a stable slope may withstand elements like erosion, landslides, or collapses [22].

In many technical and environmental applications, stability assessments are essential. These applications range from managing natural slopes in hilly or mountainous areas to designing infrastructure projects like buildings and roads [23]. Engineers assess stability and take appropriate action to preserve or improve it using monitoring tools, field research, and mathematical models.

Figure 2: Soil and rock consultants carry out analysis [23]

1.3. Slope failure types

Slope geometry, material qualities, water content, and external triggers are some of the elements that affect the original characteristics of each form of slope failure. To evaluate the risks connected to particular slopes and put in place suitable mitigation measures [24], geotechnical engineers and geologists must have a thorough understanding of various failure types.

- **Translational Slide**

In this type of failure, a mass of soil or rock moves along a roughly planar surface. Translational landslides are characterized by a distinct sliding mass and influenced by various factors such as stress distribution and slope weaknesses. They begin near the slope's base, and stress distribution limits the shear stress required for slope-parallel sliding in uniform slopes, making pre-existing weaknesses necessary for sliding to occur [25].

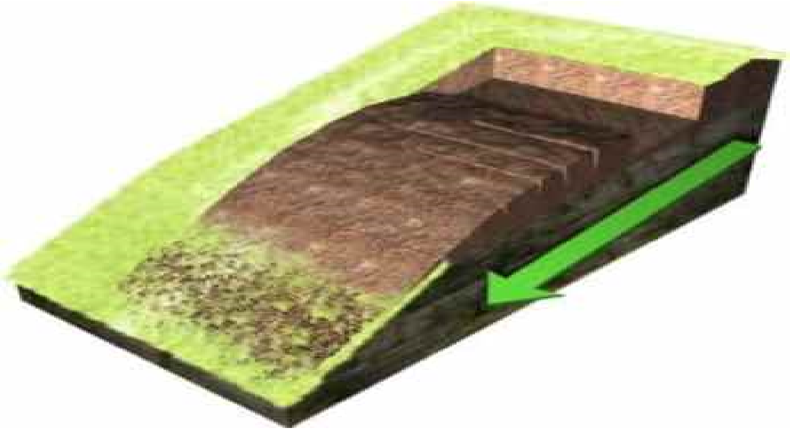

Figure 3: Translational Failure [26]

- **Rotational Slide (Slump)**

Rotational failure mostly occurs in homogenous fine-grained soils or rocks of highly disintegrated/ weathered type. The failure surface shows rotation along the slip surface, and the shape of the slip surface is curved. Failure occurs at a point of rotation of mass movement, which is parallel to the slope and moves downwards. Rotational failures most commonly occur in three types. Rotational failure can occur in finite slopes such as earthen dams, embankments, man-made slopes, etc [27].

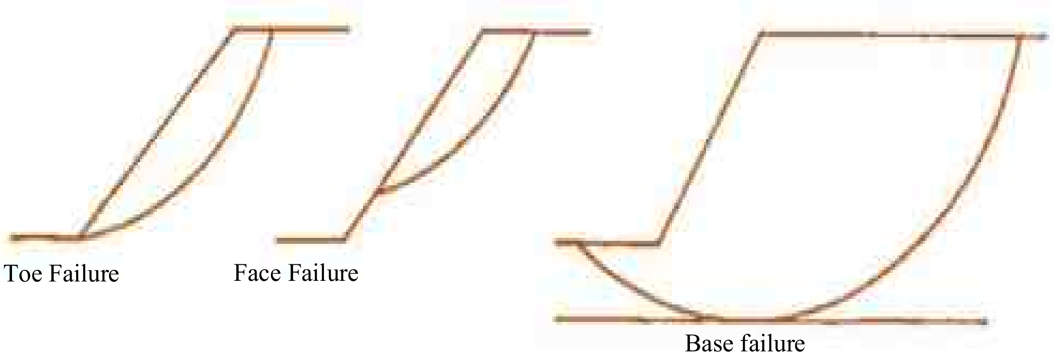

Figure 4: Types of Rotational Failures [28]

- **Debris Flow**

Debris flow involves the rapid downslope movement of a mixture of soil, rock, water, and organic material. It is often triggered by heavy rainfall or rapid snowmelt.

Figure 5. Rotational Failure [29]

- **Mudflow**

Similar to debris flow but with a higher water content, mudflows consist of a slurry of fine-grained materials moving downhill Mud flows can occur due to volcanic eruptions. In areas near the volcano, lava and pyroclastic flows are common. As the Mud flows move downstream, the solid particles in the mixture become smaller and can mix with water from rivers, lakes, rainfall, melting snow or ice, or eroded soil. This results in the formation of homogeneous mud mixed with rocks.

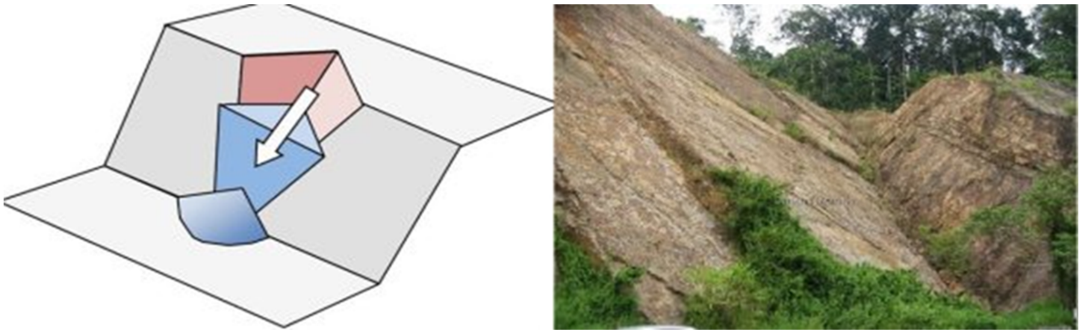

Figure 6. Wedge Failure [30]

- **Rockfall**

Rocks or fragments of rocks can come loose and fall down a slope, either by bouncing or free-falling. This type of failure is commonly seen in steep rocky areas. Detachment occurs when a rock compartment loses contact with the surface it was previously attached to on the cliff. This detachment happens due to a failure process that sets the rock compartment in motion. The failure process usually happens by sliding, but other types of failures such as tensile, bending, and buckling failures can also be a contributing factor [31].

- **Toppling**

The entire mass of rock rotates outward from its base, leading to a toppling failure. This is typically observed in rock formations with planes of weakness. Toppling instability is a common type of failure for rock slopes. In some cases, external factors can trigger secondary toppling instabilities. One type of secondary toppling failure is known as slide-toe-toppling failure. In this type of instability, the upper and toe parts of the slope are at risk of sliding and experiencing toppling failure [32].

- **Creep**

Creep is a slow, gradual downslope movement of soil particles [33]. It is commonly influenced by freeze-thaw cycles, wetting-drying, and gravity.

- **Complex Failures (Compound Failures)**

Compound failures involve a combination of different failure types. For example, a rotational slide may evolve into a debris flow, showcasing the interplay of multiple failure mechanisms.

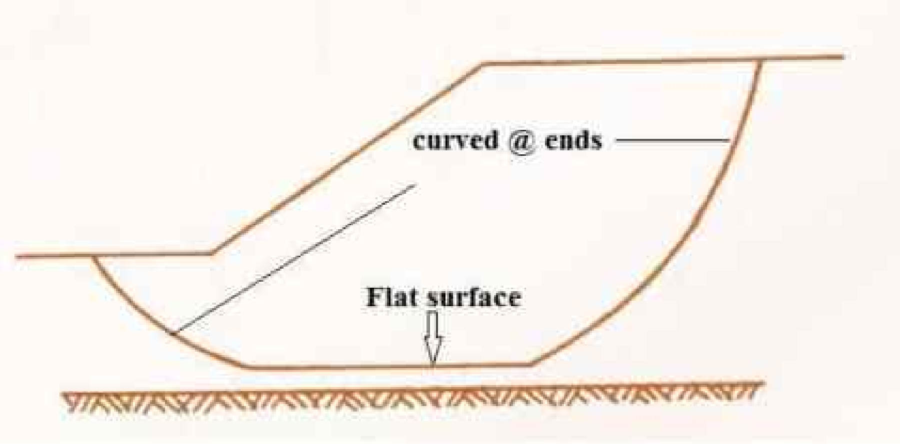

Figure 7. Compound Failure [34]

2. Literature review

Natural hazards manifest as sudden events causing severe damage to both life and property. These hazards, including floods, cyclones, mass movements, volcanic eruptions, earthquakes, droughts, tsunamis, wildfires, and locust infestations, pose significant threats to the environment and human life [35]. The document discusses safety concerns in room and pillar coal mines, particularly during retreat mining. It proposes a semi-quantitative methodology to manage risks, identifying critical factors influencing collapses. Implemented in Tabas Central Mine in Iran, this method analyses various scenarios for associated risks. It uses engineering expertise, mining experience, and literature to assign numerical scores indicating collapse probabilities. The user-friendly and comprehensive method aids mine design in mitigating collapse risks, despite uncontrollable geological factors [36]. In particular, mechanised tunnelling is examined with the dangers involved with tunnel and subterranean building projects. Taking into account probability and effect considerations, it combines geological investigations and expert advice to determine eight risk groups. Multi-criteria decision-making (MCDM) strategies, such as the Fuzzy Analytical Hierarchy Process (FAHP), are used to prioritise risks. Gas emissions and clay clogging rank lowest among the dangers associated with the Golab Tunnel in Esfahan, Iran, whereas squeezing and face tunnel instability rank highest. Through MCDM sensitivity analysis, the study recommends enhancing FAHP procedures in the future for more successful analysis [37]. The drilling and blasting method is a popular choice for rock breakage in surface or underground mines due to its flexibility and low investment costs. However, flyrock is a significant disadvantage, potentially leading to fatalities and damage to equipment. To minimize flyrock risk, mining engineers must identify causing events and their probabilities and severities. A combination of fuzzy fault tree analysis and multi-criteria decision-making methods is used to identify these events. The resulting risk matrix identifies design error, human error, and natural error as the main causes of flyrock in surface mines. The risk number of flyrock occurrences due to these events is calculated using probabilities and severities. This approach is useful for analysing various events contributing to flyrock occurrences and is highly valid for risk assessment in surface mines. Future research should use AND gates for connecting basic events to intermediate and top events [38]. Resilience is the ability of a system to resist, adapt, and recover from disruptive events. It is the first step in resilience management, but it faces challenges such as limited data accessibility. To analyse system resilience more precisely, the effect of observed and unobserved covariates should be considered in the collected resilience database. This study proposes a formulation to model the effect of these covariates on complex system resilience. It is applied to a surface mine's transportation system, showing that a failure or disruption in the transportation system has a 97.43% probability of being resilient against failure events. To increase or maintain the resilience of the mine's transportation system, management should focus on subsystems with low reliability, maintainability, and supportability. The application of resilience in the mining industry will help minimize downtime and reduce costs [39]. Among these, landslides stand out as the most frequently occurring geohazard, exerting a considerable impact on both the environment and human lives. Characterized by their transient nature, landslides can bring about dramatic changes to landscapes and destroy life and property. In a precise sense, landslides involve the rapid movement of sliding earth material, detached from the stationary part of the slope by a distinct plane of separation due to slope failure, influenced by gravity [10]. The word cloud in Fig 8 represents the most and least words frequently used by the researchers. According to this word cloud that is generated with the help of the Web of Science (WOS), the larger the size of the word, the more frequently it has been used in research, and the smaller the size of the word, the less it has been used.

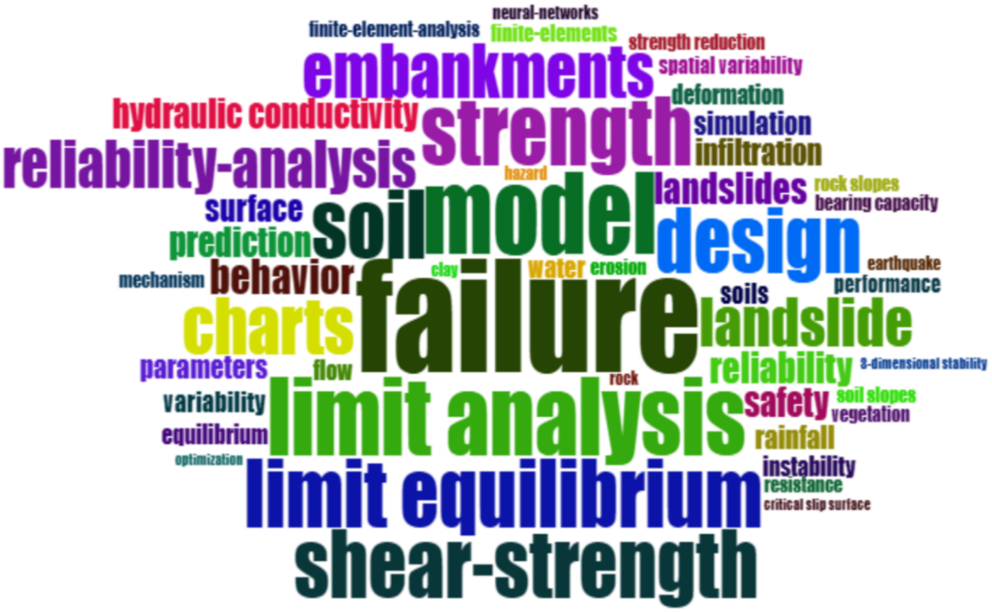

Figure 8. Word cloud illustrates the most and least frequently words used from WOS

The escalating population in landslide-prone areas has exacerbated the problem of deaths and injuries caused by landslides. Researchers, such as Varnes (1981) and others over the past three decades, have extensively worked on landslide hazard and risk zoning, employing various approaches. Slope instability processes are influenced by local geomorphic, hydrologic, and geologic conditions, with modification occurring due to geodynamic processes, vegetation, land-use practices, and human activities [40]. Approaches to potential slope stabilization problems, initially outlined by Gedney and Weber (1978) and later modified by Holtz and Schuster (1996), involve avoiding the problem, reducing the forces causing movement, and increasing the forces resisting movement. To diminish driving forces, constructing surface and sub-surface drainages becomes crucial for slope stabilization. Various researchers, including Forsyth and Bieber (1984) and Carrara (1989), have proposed diverse techniques for external stabilization systems, incorporating geogrids, good surface drainage, and drainage wells [41].

Slope stability analysis is vital for identifying endangered areas, delineating potential failure mechanisms, understanding slope sensitivity to trigger mechanisms, and suggesting viable mitigation measures. Various researchers, such as Sharma et al. (2019), Singh and Thakur (2019), and Kadakci Koca and Koca (2020), have employed different methods, including Bishop analysis and limit-equilibrium methods, for slope stability analysis. Understanding the causes of instability is crucial in slope instability investigations [42]. The analysis involves evaluating and estimating slope movement while proposing safe and economic designs to maintain slope equilibrium conditions. Researchers like Hoek and Bray (1981), Wyllie (1991), Norrish and Wyllie (1996), and Wyllie and Mah (2004) have developed effective rock stabilization designs.

Mitigating the impact of landslides requires a detailed understanding of physical processes and historical information. Researchers, including Đuric et al. (2017), Luo et al. (2017), Song et al. (2019), Huang et al. (2019), and Chen et al. (2020), have adopted various mitigation strategies [16]. This study focuses on two major landslide events along the NH-205 in Himachal Pradesh, India, aiming to develop urgent mitigation strategies for these severe slope failures. The study area is critical due to the economic activities and strategic importance of NH-205, and the research aims to delineate unstable segments, recognize potential failure mechanisms, and propose effective mitigation measures. The study is a unique attempt to evaluate mitigation design parameters for specific landslide sites, contributing to the understanding of landslide impacts on strategic transport routes in the northwestern Himalayan terrain [43].

2.1. Geotechnical Studies on Himalayan Slopes

Geotechnical studies in the Himalayas have been crucial in understanding the region's complex geology. The Himalayas, characterized by their young and dynamic tectonic activity, present unique challenges to slope stability that demand thorough investigation. Researchers explore different levels of the geotechnical characteristics, contributing significantly to the comprehension of the terrain and the risks associated with it [44]. Lithology, or the study of rock composition and characteristics, stands out as a crucial factor in understanding the behaviour of Himalayan slopes [45]. Different rock types, each with its distinct properties, respond differently to weathering processes and external forces. Through extensive field surveys and laboratory analyses, researchers have checked the lithological variations across the Himalayan landscape, laying the groundwork for assessing the stability of slopes. Weathering, another crucial factor, has been marked in geotechnical studies as it directly influences the mechanical properties of rocks and soil [46]. The country scientific production in Figure 9 is from Web of Science which shows the most and least amount of literature review was done by the researcher in this topic. In this figure, it is shown that the darker the blue colour becomes, the more studies have been done on this topic and vice versa.

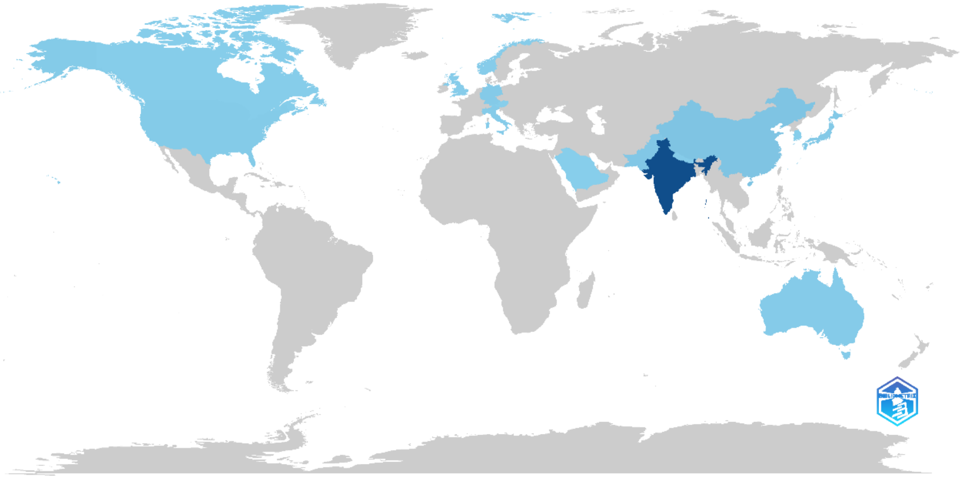

Figure 9. Country Scientific Production in the Himalayan Region from WOS

The Himalayan region, subject to intense monsoons, freezing temperatures, and rapid temperature changes, experiences weathering processes that can compromise slope stability. By examining the extent and mechanisms of weathering, researchers have gained insights into the vulnerability of slopes to erosion and failure.

2.2. Lessons from Previous Landslide and Rockfall Events

A review of documented landslide and rockfall events in the Himalayan region, particularly in Himachal Pradesh, can offer valuable lessons. Examining the causes, consequences, and responses to past incidents contributes to a comprehensive understanding of the challenges associated with slope stability [47]. By synthesizing insights from these related works, the proposed study on the SE-facing escarpment of Manikaran can build upon existing knowledge and contribute to the development of effective slope stability assessment and mitigation strategies along the NH-Kiratpur to Manali New Highway.

Table 1: Number of Country Scientific Production from WOS.

REGION	Frequency	REGION	Frequency
INDIA	159	NEPAL	4
CHINA	13	NORWAY	3
PAKISTAN	9	UK	3
JAPAN	7	CANADA	2
GERMANY	6	AUSTRIA	1
USA	5	SAUDI ARABIA	1
AUSTRALIA	4	SOUTH KOREA	1
ITALY	4		

Among analytical approaches, traditional limit equilibrium techniques can be used to produce precise safety factors for engineering reasons. The reliability of these techniques is demonstrated by their integration with modern software programs, such as PLAXIS and Geo-slope. Nevertheless, due to the development of quick computing solutions, numerical techniques have been widely used recently even though analytical procedures are simple to use and offer an intuitive way to a final answer [31]. The use of FEM and methods based on the plasticity limit analysis upper-bound theorem are the principal applications of numerical methods. However, even though the fact that these techniques estimate slope stability, which is reasonable and frequently more reliable than limit equilibrium analyses, putting them into practice requires a lot of computing power and advanced software, which isn't always feasible, particularly when there isn't much time to prepare a geotechnical report or in field circumstances. Slope stability charts are a useful tool for quickly estimating slope stability in certain situations [48]. This method was first presented by Taylor, who used a dimensionless parameter Ns, a slope angle β, and an angle of internal friction φ to estimate safety factors. Several stability charts were proposed by several investigations that followed this first proposal, and these analyses generated a fairly accurate initial estimate of slope stability. Artificial neural networks, support vector machines, and genetic algorithms are increasingly widely used in addition to the previously described analytical and numerical approaches, which are founded on well-established and conventional concepts [49]. This is due to the significant advancement of artificial intelligence techniques, in assessments of slope stability. To estimate safety aspects, all of these techniques offer dependable and user-friendly instruments. In addition, several methods like genetic algorithms produce clear mathematical formulas for estimating a slope safety factor. The safety factors and the effect of input parameters can easily estimated and estimated with the help of these equations, which are based on the nonlinear dependency of safety factors on different geometrical slope feature parameters of soil [50].

The average rainfall during the monsoon season is approximately 100 cm, with intensity decreasing from Punjab plain in the southwest to Manali in the northeast [45]. Among the two selected sites, the area adjoining the study area receives the maximum annual rainfall, averaging about 150 cm, followed by the Bilaspur sub-segment with an average of 140 cm. Precipitation during one month of the monsoon season can exceed 650 mm, with daily rainfall ranging from 40 to 120 mm. The geological composition along and adjacent to NH-205 comprises varied lithological assemblages, featuring different geological formations and groups ranging in age from Tertiary to Proterozoic [51]. The soil and debris exposed in the entire road section mostly consist of debris deposits and drifted soil, developed predominantly on moderately reposed slopes.

By evaluating the regular closure of this crucial road during the monsoon season and the frequency of reported landslip accidents, the study region was selected [52]. The chosen path is crucial for handling the large number of tourists that Himachal Pradesh receives year-round because it is the main feeder trunk to different regions of the state and bordering states for the transshipment of necessities [44]. These soils, 2–5 meters thick, are primarily derived from scree/talus and hill-wash material. According to the geological map of India prepared by the Geological Survey of India (GSI) and the macro-level seismic zoning map of the Bureau of Indian Standard (BIS 1993–2002), the entire stretch of NH-205, transecting the outer and lesser Himalaya zone, is seismically active and falls within Zone IV and Zone V. This seismic activity adds layer of complexity to the geological considerations for the study area [48].

The primary goal of the study was to maintain stability in the sensitive zones of the NH-205 by defining the parameters for the mitigation design and planning the slopes to allow for safe vehicular movement throughout the year with appropriate maintenance and minimum economy. The correct interpretation of a landslide's surface feature to measure a wide range of soil qualities, samples of soil were subjected to various laboratory procedures [53]. Certain characteristics of the soil are inherent in its composition and remain unaffected by sample disturbance, whilst other characteristics rely on the soil's composition and structure and can only be effectively evaluated on samples that have not been significantly disturbed [54]. The lab tests listed below were carried out on samples to ascertain the input parameters for slope design: The bulk density of the soil, or in-situ density; moisture content; grain size analysis; Atterberg limits, expansion index test; direct shear test; and unconfined compression test are the first five tests. However, the majority of the rock samples were taken from "undisturbed" or "disturbed" areas of the failed slope across the main highway and underwent the unconfined compression test and the direct shear test in a laboratory setting to ascertain the rock strength. To estimate the compressive strength of in-situ rocks at discontinuity surfaces, the Schmidt Hammer Test was also employed in the field [14].

Among the many popular techniques for slope stability, the stability analysis of circular failure was done using Software GEO5, Hoek and Bray's Circular Failure Charts (1981) [51], and Bishop's Simplified Methods of Slices (1955). Hoek and Bray's (1981) analytical formulas were used to do the stability analysis of plane failure and wedge failure. These calculations were based on the location of stress cracks, the slope and sliding plane geometry, and the wedges defined by discontinuity planes projected stereographically. A thorough exercise in calculating the FOS of the failed slope and the FOS of the slope on reinforcement with bolts and anchors was completed using the input parameters mentioned above [55]. The findings from the slope stability study, which was conducted for the plane and circular failure modes utilizing the approach recommended by Wyllie and Mah (2004), were used to recommend mitigating measures. Exercises for creating anchors, rock bolt patterns, and anchor designs were also devised and recommended.

3. Mitigation

Mitigating the impact of rockfalls involves employing methods that permit rocks to fall while minimizing the resultant damage and ensuring uninterrupted traffic flow. These strategies encompass the utilization of catchment benches, ditches, berms or fences, draped wire mesh, and rock shed structures. Catch benches and ditches emerge as the most cost-effective solutions in this study, acting as effective traps to contain fallen rocks. However, the feasibility of rock traps hinges on the availability of adequate space at the slope's toe [56]. The narrow roads at the studied sites pose challenges for implementing solutions such as retreating rock cuts through blasting to create ditches and benches due to associated costs and disruptions. While berms are highly effective in capturing rockfalls, their application is constrained by similar considerations. An alternative approach is the use of wire mesh draped over the rock face, preventing the descent of small rocks while allowing larger rocks to descend gradually with low kinetic energy, reducing the risk of bouncing onto the highway. Although draped mesh offers an economical solution, it necessitates regular inspection and maintenance, particularly when dealing with larger rock failures that could result in significant damage [57].

Catch fences or barrier fences present another effective method for enhancing ditch capacity, both in terms of volume and width, especially when existing ditches prove insufficient [42]. These fences typically exhibit an estimated energy absorption capacity of 100 KNm, equivalent to a 250 kg rock moving at approximately 20 m/s. Fences, including jersey barriers, are particularly well-suited for situations with limited space. It is imperative to line the ditch with an energy-damping material such as gravel or sand and conduct routine inspections and maintenance to remove fallen rocks. A CRSP (Catchment, Runout, Size, and Probability) analysis can be conducted to analyse the effectiveness of these mitigation measures. This analytical approach helps assess the performance and efficiency of the implemented strategies in containing and managing rockfalls, providing valuable insights for ongoing improvements and maintenance protocols [58].

4. Discussions on case studies

The engineered cut slope failures in Korea triggered by rainfall through two case studies. It introduces a novel approach that extends traditional limit equilibrium analysis to unsaturated conditions using a generalized effective stress framework. By combining soil-water retention curves and soil strength characteristic curves with the same hydromechanical parameters, the methodology requires minimal additional parameters. Three unsaturated hydromechanical parameters are introduced to conduct slope stability analysis under variably saturated conditions. Reconstructs failure occurrences at two slopes in Korea using site geology, observed shear strength, and soil-water retention curve data. It also uses recorded rainfall data [59]. According to the investigation, as the factor of safety got close to its minimum, or 1.0, failures happened in a variety of saturated circumstances. Within a few days and a few percent, respectively, the framework predicts failure times and factor of safety with high accuracy. This concludes that, in contrast to conventional methodologies that rely on saturated conditions and conservative assumptions, the expanded hydromechanical framework can precisely analyses and predict the failure of unsaturated engineered slopes under transient rainfall conditions [60].

The geodynamic properties of the terrain and the weak rock structures cause frequent instability and landslides in the Himalayan region, especially in the Lower Siwalik formation. 1999 saw a large landslide in the Amiyan area that blocked the Gaula River and severely damaged nearby infrastructure. Slope instability in the Amiyan region in Kathgodam, Nainital, Uttarakhand, is investigated using finite difference method for the numerical simulations, laboratory tests, and field surveys. Using the finite difference method, the research determines that the Amiyan slope is prone to risk and suggests taking precautionary steps to reduce it. Three-dimensional modeling techniques were used to assess a rock slope's stability. After a liner was applied, the estimated Factor of Safety (FOS) was 1.52, suggesting critical stability because of the weak rock. Lower benches gradually failed due to constant high load and hydrostatic conditions, while above benches remained stable. All along the slope, tension fractures were visible, but the most noticeable ones were found in the lower benches, where accumulation of stress caused them to spread. The possibility for stabilizing the rock mass with adequate liner thickness is suggested by a large increase in FOS, which can be achieved by the use of liners in susceptible zones [61].

Predicting prospective landslide damming locations in the Satluj Valley, Northwest Himalaya, is the main goal of the study. Landslides have historically caused considerable losses and deaths in this area. With a total volume of around 26.3 6.7 x 106 m3, the research assesses 44 active landslides in the area and finds five of them as possible landslip damming locations [62].

The report examines rainfall's effect on landslides and damming. Four of five landslides have unstable slopes, and one is meta-stable. Understanding variables that affect slope stability is crucial, such as in-situ field stress and soil's internal friction angle, and Factor of safety <1 whereas, the remaining one is meta-stable i.e., 1≤FS≥2. Conclusions are critical given increased rainfall and flash flooding since 2010, and the risk of material flow from these landslides [63].

In the Indian Himalayas, close to Pipalkoti, landslides and slope collapses are being studied along a section of the Chamoli–Badrinath route. To investigate slope characteristics and soil/rock qualities the region was separated into zones and carried out field surveys, mapping, data gathering, and laboratory testing. They modelled slope behaviour and failure processes using numerical simulations and a 2D finite element method, using shear strength reduction analysis to identify crucial components. The limits of conventional analytical techniques were highlighted by the results, which demonstrated considerable instability in the rock/debris slide slopes and good alignment between models and field measurements. finite element modelling is a useful technique when based on reliable data, landslide modeling for hazard assessment and mitigation. The comparison of material characteristics between debris slides and stable debris slopes revealed variations in cohesiveness, friction angles, and grain size distribution; however, further case studies are required for validation [64].

Slope instability along NH-05 at Jhakri, Himachal Pradesh, India, is the subject of the study. After assessing the slope's morphometry and features in the field, landslides with a height of 27.26 m and a post-failure angle of 63° were discovered to be moving NW–SE. A coarse to fine loamy soil devoid of surface vegetation and susceptible to erosion in the event of heavy rainfall was revealed by the soil samples that were obtained. Cohesion (c) and friction angle (Phi), determined by shear testing, were 10.28 kPa and 18.8°, respectively. According to a 2D limit equilibrium model (LEM), there is instability, with a safety factor of 0.43. 1.2 factor of safety (FOS) reinforced bench slope stabilization using soil nailing is advised. A semi-circular slip surface was discovered after more research, with the crest suffering significant damage after the landslip. Cohesion, friction angle, and unit weight are parameters that are evaluated following a landslip; this leads to a FOS of 0.432, which denotes instability. The proposed adjustments comprised soil nailing in addition to 4 m interval benches with a slope height of 10 m at a 70° angle. The soil nailing technique achieved FOS values of 1.106 and 1.101 for bench slope and soil nailing methods, respectively, showing stability with the suggested measures [65].

The slopes are assessed with the FOS against sliding. The topography and material qualities along the whole length of NH-205 vary greatly, contributing to the slope conditions. The material's shear strength varies when its physical-chemical characteristics, moisture content, and environmental factors change. More attention is being paid to the requirement for accurate models to mitigate the many types and dimensions of landslides that are exposed and/or anticipated to occur in the future due to the distribution of different types of material with inherent diversity in physical properties [66]. According to the findings of the current study, the fundamental physical characteristics of the slope-forming material, such as its shear strength capability, slope geometry, and structural features, which significantly lower its effective shear strength, are the principal reason behind the NH-205's parts' fragility. Additionally, the NH-205's slope instability is a result of human interaction altering the slope geometry [67]. The mitigation design parameters of slope failures including rock slope at Panjpiri plane failure and Nalayan circular failure were completed concerning the geotechnical aspects of chosen landslides. The results of the slope stability analysis of the Panjpiri plane failure, in which a block of ferruginous micaceous sandstone measuring 12 9 4.5 9 1.5 m in the middle Siwalik formation collapsed, indicated that the conditions for dry slope, wet slope (zw = 0.5 m), and wet slope (zw = 2.25 m) were FOS 1.22, 1.17, and 1.03, respectively. The following mitigating methods were recommended based on the determined FOS: (i) rock bolting; (ii) reinforced concrete dowels; and (iii) trim blasting to remove overhanging rock.

5. Conclusions

In conclusion, assessing and mitigating unstable slopes represent a critical domain within geotechnical engineering, demanding a comprehensive and multidisciplinary approach. The understanding of geotechnical properties, environmental factors, and human activities is paramount in deciphering the complexities of slope stability. Analytical methods, numerical modeling, and advanced monitoring techniques provide valuable tools for assessing slope conditions with increased accuracy and predictive capabilities. Mitigation strategies, ranging from surface stabilization through vegetation and erosion control to structural interventions like retaining walls and soil reinforcement, underscore the importance of addressing instability at its root causes. Drainage improvement measures play a crucial role in managing pore water pressure, mitigating one of the key factors contributing to slope failures. The integration of early warning systems further enhances proactive risk management, enabling timely responses to evolving slope conditions. Continuous research and technology are imperative to refine existing methodologies and develop sustainable solutions to mitigate the challenges posed by unstable slopes. The synthesis of traditional engineering practices with innovative approaches ensures a holistic understanding of slope stability, promoting the resilience of infrastructure and the preservation of human lives and the environment. As we navigate an era of increasing urbanization and environmental changes, the lessons learned from slope stability assessment and mitigation contribute significantly to fostering resilient and sustainable landscapes for future generations.

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مروری بر تجزیه و تحلیل و استراتژی های کاهش برای مدیریت خطر زمین لغزش: مطالعات موردی نائینیتال، دره ساتلوج، پیپالکوتی، جاکری، پنچپیری در منطقه هیمالیا، هند

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چکیده:

زمین لغزش‌های تأثیرگذار بر خسارات جانی و مالی به یک تهدید جدی در کشورهای مختلف در سراسر جهان تبدیل شده است که اهمیت پایداری شیب و کاهش آن را برجسته می‌کند. روش‌ها و ابزارهای مورد استفاده برای تحلیل پایداری شیب، از روش‌های تعادل حدی سنتی تا تکنیک‌های مدل‌سازی عددی جهانی. بر اهمیت جمع‌آوری داده‌های دقیق و قابل اعتماد، از جمله بررسی‌های ژئوتکنیکی، در توسعه ارزیابی‌های دقیق پایداری شیب تمرکز دارد. علاوه بر این، چالش‌های مرتبط با پیش‌بینی و کاهش خرابی‌های شیب، به‌ویژه در محیط‌های پویا و پیچیده را نیز بررسی می‌کند. استراتژی های کاهش برای شیب های ناپایدار به طور سیستماتیک از محققان مختلف مورد بررسی قرار گرفت، که شامل اقدامات سنتی و نوآورانه بود. روش‌های سنتی، مانند دیوارهای حائل و سیستم‌های زهکشی، استراتژی‌های کاهش با تأکید بر اقدامات پیشگیرانه و مداخلات اصلاحی مورد بررسی قرار گرفتند. اینها شامل پیاده‌سازی راه‌حل‌های مهندسی مانند سازه‌های شیب‌دار و تکنیک‌های آزمایشگاه ماتریس (MATLAB) همراه با تحلیل جامع چهار ابزار برجسته ارزیابی پایداری شیب است: رتبه‌بندی جرم سنگ (RMR)، رتبه‌بندی جرم شیب (SMR)، و تعادل حد. روش (LEM). تحلیل تطبیقی این ابزارها، نقاط قوت، محدودیت‌ها و حوزه‌های کاربردی مربوطه را برجسته می‌کند و بینش‌های ارزشمندی را برای محققان، نویسندگان و متخصصان فراهم می‌کند تا انتخاب‌های آگاهانه بر اساس الزامات خاص پروژه داشته باشند. برای اطمینان از ایمنی و پایداری زیرساخت های عمرانی، درک کامل عوامل زمین شناسی، ژئوتکنیکی و محیطی در ترکیب با فناوری های پیشرفته مورد نیاز است. علاوه بر این، نقش مهمی را برجسته می‌کند که ارزیابی پایداری شیب و کاهش نقش مهمی در مهندسی عمران برای توسعه زیرساخت‌ها و استراتژی‌های کاهش بازی می‌کند.

کلمات کلیدی: سنجش از دور، مانیتورینگ، تثبیت سطح، اقدامات ساختاری، بهبود زهکشی.