Analyzing the Geotechnical Aspects of Landslide Events and Disaster Vulnerability along CPEC route in Gilgit Baltistan

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Abstract. This study delves into the examination of landslides induced by shifts in land-use patterns within the CPEC, with a specific emphasis on exploring mitigation strategies and identifying influential factors. The CPEC, linking southwest China with Pakistan, faces challenges due to landslides, which impact priority infrastructure projects like roads and railways. We propose an evaluation index system to quantitatively assess landslide risks in the corridor. The repercussions of landslides on human habitation and the integrity of natural landscapes underscore the necessity of a comprehensive understanding of their origins, consequences, and effective mitigation approaches. Frequent landslides pose significant risks to countries and regions, stemming from the interplay of internal and external Earth processes. They are a common geohazard, inflicting damage on infrastructure, buildings, and transportation systems, leading to human and economic losses. Our research scrutinizes the occurrences and Susceptibilities of landslides along the CPEC route in Gilgit Baltistan, presenting mitigation strategies grounded in a synthesis of existing literature and pertinent case studies. The study underscores the imperative of harmonizing environmental sustainability with economic development in this pivotal region, emphasizing the need for a balanced and integrated approach to ensure the longevity and resilience of both the natural environment and developmental initiatives.

Keywords: Landslides, China Pakistan Economic Corridor (CPEC), Gilgit Baltistan, Karakorum Highway (KKH), Environmental sustainability, Slope stabilization.

1. Introduction

1.1 Background

Pakistan, located at the intersection of tectonic plates, faces multiple hazards, including earthquakes, floods, droughts, water-logging, salinization, and recurrent landslides. Landslides pose a significant threat to natural landscapes and human settlements, requiring a thorough understanding of causes, impacts, and mitigation. Environmental destruction leads to hazards like slope failure, floods, and soil erosion, fueled by hydrological, geological, and atmospheric factors. (Rahman, Khan, Collins, & Qazi, 2010).With increasing populations and urbanization in vulnerable areas, the frequency and severity of landslides rise, causing environmental degradation and socio-economic disruptions. Landslides, varying in their intensity, can cause extensive damage to buildings and transportation infrastructure along their path. Developing countries, including China and Pakistan, face significant risk from landslides, especially in the construction of the CPEC. Additionally, these countries have experienced numerous strong earthquakes in the past two decades, contributing to disaster losses that exceed the global average, according to data from the global disaster database.

This research aims to analyze landslide occurrences and vulnerability along the CPEC, proposing mitigation strategies. Through literature and case studies, this study fills knowledge gaps, guiding future research and aiding policymakers in sustainable land management.

1.2 Significance of the Study

This research paper investigates the occurrence of mass movement linked to changes in land use, focusing on mitigation strategies and other factors. The importance of gaining insights into this phenomenon is closely tied to the potential impact of landslides on human communities, economic endeavors, and ecosystems. Frequent rainfall,

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particularly during the monsoon season, often triggers landslides. These events not only lead to road closures and damage to both private and public assets but also result in the tragic loss of human lives (Riaz, Wang, Basharat, & Takarav, 2019).Moreover, the research paper also includes causes and triggers, slope stability mechanisms and case studies. The study specifically helps in tackling future challenges and recommends geotechnical analysis of areas along CPEC in Gilgit Baltistan.

1.3 Objective of the study

- Analyze the geo-technical aspects of Land sliding along the KKH.
- Evaluate how often landslides occur and how serious they are in the northern areas of Pakistan.
- Investigate impact of landslides on infrastructure and transportation systems, particularly along the KKH.
- Identify proactive measures to mitigate the threat of landslides in the topographically active areas of Pakistan.
- Provide recommendations for enhancing resilience to landslides, especially in regions crucial for the CPEC.

2. Geotechnical characteristics of the Gilgit Baltistan region

2.1 Geological Overview

The region features granitic formations derived from magmatic plutons and smaller geological bodies. Examples include the Gilgit River, tonalite, granodiorites, granites, hornblende gabbro, granitic gneiss, quartz diorite, and hornblende-rich amphibolite. The unit includes Jurassic to Paleozoic rocks that make the Darkot-Karakoram Metamorphic Complex, which contains amphibolites, gneisses, ultramafic rocks, chalt volcanic, and Yasin Group comprising volcanic sediments, slates, and green schist facies. The Mesozoic to Paleozoic rocks comprise the metasedimentary units with predominant volcanic rocks on its portion along the northern suture mélange; the less dominant are limestone, red shale, and conglomerates. In fact, the curvature of the head scarp does suggest that such landforms were created by tensile pull-apart forces. Diverging contours, abnormal drainage patterns, long ridges, and isolated knobs strongly indicate of mass movements. (Muhammad Farooq Ahmed, 2021).The region faces prehistoric rockslide avalanches due to high seismic activity from active thrust faults, delicate geological conditions, and adverse seasonal weather changes.

2.2 Seismic activity

Pakistan is situated geographically on the edges of the world, which is very seismically active known as the Himalayan-Karakoram-Hindukush earthquake belt. This region has been a frequent site of catastrophic seismic events over an extended period. Both literature and historical data consistently highlight the recurring occurrence of devastating earthquakes across different segments of the entire Himalayan system (Shahzada Khurram, 2021). Numerous studies indicate that the northern and western regions of Pakistan are particularly prone to high levels of seismic activity.

2.3 Soil types and properties

The CPEC spanning over 3000 kilometers from Kashgar to Gwadar Port, traverses diverse soil types in various Pakistani regions. Predominantly, Soil texture includes 35% of silt loam,30% of sandy loam,20% loam,7.5% loamy sand,5% silt clay loam and finally 2.5% silt clay. Soil properties vary due to spatial and temporal factors, influenced by intrinsic and extrinsic elements. The high altitude and climatic conditions in Northern Pakistan contribute to diverse textures, mineralogy, and soil fertility. Altitude and topography significantly impact inherent soil fertility and erosion. Precipitation, snowfall, and temperature variations affect soil organic matter accumulation and decomposition. Cultivable soil samples from Dasso village (6100-6500ft) and forest/pasture samples from Kutwal (9700-10200ft) and (10600-10900ft) were collected (Khan, 2019).

Table 1: Properties of soil sample from the site (Khan, 2019)

*Note: * indicates p< 0.05(5%),** indicates p< 0.01(1%), *** indicates P< 0.001 and NS means Non-Significant*

Parameters	Land Use
Soil moisture (%)	11.8^{***}
Bulk density(g/cm^3)	1.9^{NS}
PH	174.6^{***}
Electrical Conductivity (uS/cm)	17.0^{***}
Soil Organic Matter (%)	3.9^{*}
Soil Organic Carbon (%)	3.9^{*}
NO_3-N (mg/Kg)	0.40^{NS}
Av.P (mg/Kg)	0.50^{NS}
Ex.K (mg/Kg)	0.60^{NS}

2.4 Weather patterns and Climate

At 3,702.19 meters (12,146.29 feet) above sea level, Gilgit-Baltistan has a Subarctic climate (Classification: Dfc) with harsh winters and cool summers. The annual temperature is -9.62ºC (14.68ºF), -30.51% lower than Pakistan's average. From 1955 to 2018, the region's annual mean temperatures ranged between 9.77 ℃ and 20.24℃, with Chilas recording the highest (20.24℃,) and Astor the lowest (9.77℃,). Descriptive statistics noted Gupis with the highest standard deviation (0.89) and Gilgit with the lowest (0.56). Upward trends in temperatures were observed in Astor, Chilas, Gilgit, Gupis, and Skardu, while Bunji showed a downward trend. Significant temperature increases occurred in Astor and Skardu, with a notable decrease in Bunji. Annual precipitation rose at all stations except Astor and Chilas, where it decreased insignificantly (Wahab, 2022).

3. China Pakistan economic corridor overviews

3.1 Economic Importance

CPEC is hailed as a significant bilateral deal, considered a game-changer for both Pakistan and China. Spanning trade routes from Gwadar, Pakistan, to Kashgar, China, CPEC involves more than just roads; this development project covers a wide range of areas, including economic and industrial zones, power plants, and fiber optic networks. By enhancing these key sectors, it's anticipated to greatly strengthen Pakistan's economic stability and growth. With a substantial investment of approximately $46 billion. CPEC is crucial for China, providing shorter routes for the western and central regions to access sea ports. It holds the potential to address key economic, social, and geopolitical issues in Pakistan (Makhdoom, Shah, & Sami, 2017).

3.2 Route and infrastructure

Within Pakistan, CPEC comprises three primary routes. Among these, the Western route spans a total distance of 2,463 km, commencing from Khunjerab and traversing through Burhan, Dera, Quetta, ultimately concluding at Gwadar. This is a major component of China's Belt and Road Initiative, which is set to bring closer regional connectivity between Pakistan, China, and the rest of Eurasia. Launched as a $46 billion deal in April 2015, by 2017 the value of investments in the project had already reached $62 billion. Therefore, in order to attain increased access for Chinese trade to the Middle East, Africa, and Europe, CPEC modernizes the infrastructure and stirs economic growth in Pakistan.

Under CPEC, various projects include railway networks, power plants, the Gwadar Port, economic zones, and social sector projects. Significantly the nationwide construction of roadway networks includes a northern section and three alignments (western, eastern, and central). The 2,700 km road network involves the reconstruction of the Karakoram Highway, Peshawar-Karachi Motorway, N-30, and the upgradation of Zhob-Quetta (Kuchlak)(N-50) Phase-I, with an expected portion of thirty four billion US dollars.

CPEC connects Gwadar and Karachi seaports with Northern Pakistan, extending to Western China and Central Asia for cargo transport, minerals extraction, energy production, and commercial activities. The CPEC roadway networks offer social and economic benefits, meeting energy demands, establishing international standard roads and railways, capacity building, and boosting employment. (Mahmood A. Khwaja, 2018).

3.3 Impacts on the Region

CPEC holds a double-edged sword for Gilgit Baltistan. On the one hand, it promises an economic boom with infrastructure development, job creation, and improved trade. The region can hope for industrial growth, strengthened regional connectivity, and valuable technology transfer (Muhammad Zahid Ullah Khan, 2019), as envisioned by experts. However, these alluring advancements come with hidden costs. Environmental degradation, cultural disruptions, and a growing dependence on China raise concerns. Economic imbalances, potential issues with transparency and governance, and even heightened geopolitical tensions could threaten the long-term stability of the region. Balancing the undeniable benefits of CPEC with these significant challenges will be crucial for ensuring a truly sustainable and prosperous future for Gilgit Baltistan.

4. Landslide Occurrence: Causes and Triggers

4.1 Natural Causes:

4.2 Geological Masters of Destabilization

Steep Slopes and Unstable Formations: Gilgit Baltistan's mountainous terrain is a natural hazard magnet. Tectonic upheavals have created fractured and weathered rock formations, which lack cohesion and are prone to movement. Like dominoes poised on edge, these slopes readily cascade down at the slightest nudge. Faults and weak planes act as insidious cracks, further amplifying the vulnerability (Qureshi, 2021).

4.3 Climatic Maestro of Triggering:

- Intense Rainfall and Snowmelt: Monsoonal downpours unleash torrents of water that infiltrate thirsty slopes, saturating them like sponges. Meanwhile, rising temperatures coax melting glaciers to weep their frozen tears, adding to the deluge. This aqueous overload reduces internal friction within the soil, transforming slopes into slippery slides.
- Freeze-Thaw Cycles: Winter's icy grip transforms water in soil pores into tiny daggers. When spring arrives, these daggers melt, morphing into pore pressures that push on slope walls from within. Imagine countless microscopic fingers relentlessly poking at a sandcastle, eventually causing its inevitable collapse. This internal sabotage is precisely what freeze-thaw cycles do to slopes (Iqbal, June 2020).

4.4 Anthropogenic Forces: Tampering with the Earth's Dance:

4.5 Construction's Uneven Footsteps:

Road construction scars the mountainside, carving channels that disrupt natural drainage and saturate slopes, turning them into soggy sponges. Each bite into the earth removes crucial support, adding stress and pushing the tipping point closer. Tunneling, meanwhile, is a poke in the Earth's honeycomb, disrupting the delicate dance of groundwater. Imagine squeezing a toothpaste tube – the pressure builds elsewhere, potentially triggering landslides through this altered equilibrium. In essence, these activities tamper with the mountain's delicate balance, inviting instability with every cut and every tunnel. (Luqman, March 2021).

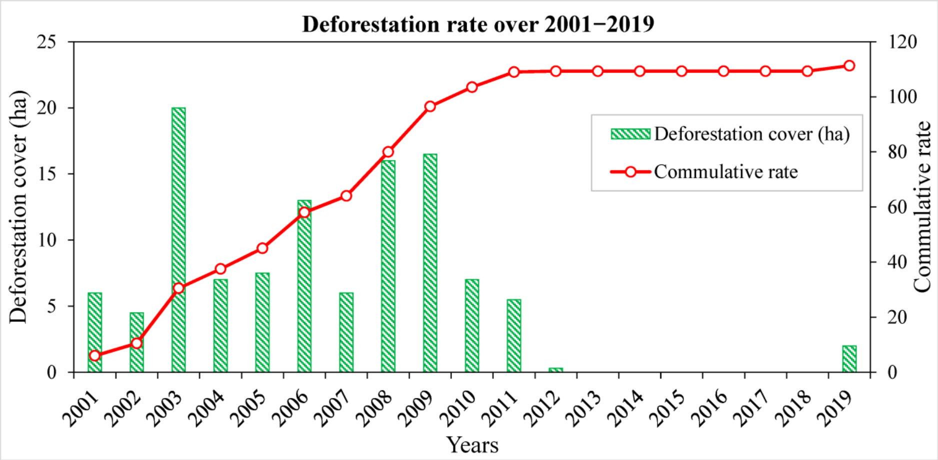
Figure I: The photo captures the dam of the Suki Kinari Hydropower Project, part of the CPEC initiative, located in the Mansehra

4.6 Deforestation and Land Use Changes: Stripping Nature's Armor:

Unsustainable Logging: Picture yanking out the tree roots that once held a slope together. That's what unsustainable logging does. Without this natural reinforcement, soil erosion accelerates, making slopes vulnerable to the slightest tremor. Think of a castle built on sand – without the sand, it crumbles.

Agricultural Expansion: Overgrazing by livestock is like a hungry army stripping away the protective vegetation cover from slopes. This leaves the soil naked and defenseless against the erosive forces of wind and rain, setting the stage for landslides. Imagine building a house on loose sand; a single gust of wind can topple it. (Qureshi, 2021).

Figure II: the graph shows deforestation in northern Pakistan from 2001 to 2019. (Global forest watch)



5. Slope Stability Mechanisms; Unveiling the Forces at Play:

5.1 Factors Influencing Slope Stability:

5.2 Material Properties

Understanding the Building Blocks: Just like the strength and quality of the paper determine the stability of the book stack, the properties of the materials composing a slope influence its behavior.

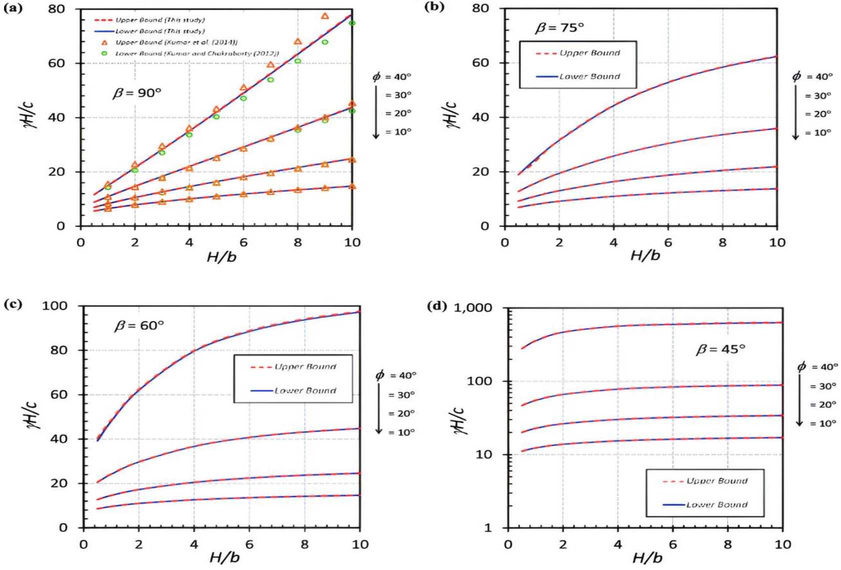
- Cohesion: The ability of soil particles to stick together, crucial for resisting shear stress and preventing landslides. Clay-rich soils have higher cohesion than sandy soils.
- Angle of Internal Friction: The maximum angle at which soil particles can resist sliding against each other. Higher angles indicate greater stability.
- Density and Unit Weight: Denser materials with higher unit weight exert greater gravitational forces, increasing the risk of failure.
- Permeability: The rate at which water can flow through the soil. Saturated soils with low permeability are more susceptible to landslides. (Ukritchon, April 2018).

5.3 Slope Geometry

The Matter of Angles and Heights: Imagine tilting the book stack further. The steeper the angle, the more likely it is to topple. Similarly, slope geometry plays a crucial role in stability.

- Slope Angle: Steeper slopes experience greater gravitational forces acting downhill, increasing the risk of failure. The critical angle, beyond which failure is likely, depends on material properties and other factors.
- Slope Height: Taller slopes have larger masses exerting pressure, making them more prone to landslides. The height-to-width ratio is a crucial indicator of stability.
- Presence of Cracks and Weak Planes: Cracks and weak planes within the slope act as preferential failure surfaces, reducing its overall strength and stability.

Figure III: Relationships between the slope height ratio and stability factor at different slope angles (b) of (a) 90, (b) 75, (c) 60 and (d) 45.



5.4 Analytical Methods and Models:

Tools for Unveiling the Unknown: To predict and prevent slope failures, geotechnical engineers employ various analytical methods and models.

- Limit Equilibrium Analysis: This traditional method calculates the forces acting on a potential failure surface within the slope and compares them to the resisting forces. If the driving forces exceed the resisting forces, failure is likely.
- Finite Element Analysis: This advanced method divides the slope into smaller elements and analyzes the stresses and strains within each element. It provides a more detailed picture of slope behavior and can be used for complex geometries and loading conditions.
- Empirical Approaches: Based on statistical analysis of past landslides and their triggering factors, these methods provide quick and practical assessments of slope stability, particularly for preliminary investigations. (Iqbal, June 2020).

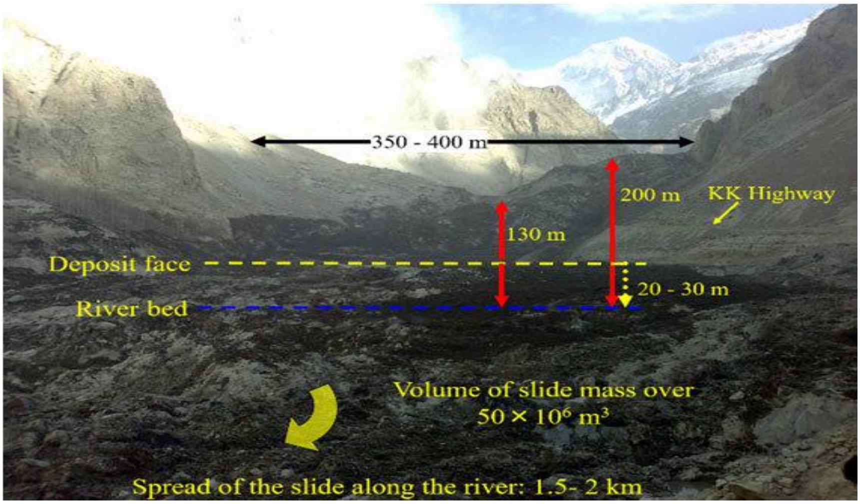
6. Previous studies and case histories:

6.1 Attabad Landslide, Hunza Gilgit Baltistan.

The Attabad landslide in Hunza, Gilgit Baltistan stands as one of the largest landslides in the history of Pakistan, occurring along the world's highest and strategically significant highway. On 4th of January 2010, a massive volume of rock slid down the slope of 45 million cubic meters, traversed a distance of 1062 meters and block the flowing Hunza River. As a result, an artificial dam formed due to the blockage. In as far as scientific terms are concerned, the Attabad rock avalanche was considered time-dependent and non-seismic, which killed 20 people and eliminated two villages, namely; Attabad and Sirat. The landslide continued 1062 meters from the origin to the limit of the deposition area, where 410 meters represented a source area. (Gardezi, Bilal, Cheng, & Xing, 2021).

Figure IV: Aerial View of Attabad Lake (Google earth).

Figure V: The land sliding point of Attabad.



The sloppy sides of the Hunza valley are composed of rock and various types of debris, such as colluvial, fluvial, and glacial deposits, and these areas typically lack significant vegetation. The valley floor is shaped by braided river channels that weave through the landscape, along with gentle alluvial fans formed by sediment from melting glaciers. These fans and debris flows from smaller valleys give the area its unique, rugged character. You can also spot traces of old glacial landforms and river terraces, evidence of the valley's long history of shifting landscapes. In this mountain desert environment, vegetation is scarce and primarily limited to irrigated agricultural patches near small villages scattered throughout the main Hunza valley. (Keith B. Delaney, 2017).

6.2 Tatta Pani Landslide area, Chilas Gilgit Baltistan:

Nestled in the formidable Karakoram Mountains, Tatta Pani boasts year-round hot springs, a geological marvel drawing visitors along the Karakoram Highway. However, its name, meaning "landslide water," reveals a vulnerability. Landslides, triggered by rain or seismic activity, threaten the vital trade route, stranding travelers. Undeterred, Tatta Pani confronts this risk with resilient measures. Engineers fortify slopes using technology, while rapid response teams stand ready to swiftly clear debris. The dance with danger becomes a choreography of resilience, as Tatta Pani navigates a delicate balance with nature's disruptive power, securing both its allure and the flow of commerce. Tatta Pani, prone to rock fall hazards, has a Pierson’s Rock fall Hazard Rating System (RHRS) value of 757. With an annual rainfall of 100 mm and a mean temperature of 16.2℃, the sloppy face varies from 205 ft. to 230 ft. with a slope angle of 85° to 88°.The area experiences peak rainfall occurs in the third and seventh month of the year. Over the last few years, severe rock falls caused prolonged traffic blockages, lasting up to one to two weeks. The Figure below illustrates the soil matrix of Tatta Pani. (Ehtesham Mehmood et al, 2022).

Figure VI (a): a scattered arrangement of rock in matrix Tatta Pani (Ehtesham Mehmood et al, 2022)

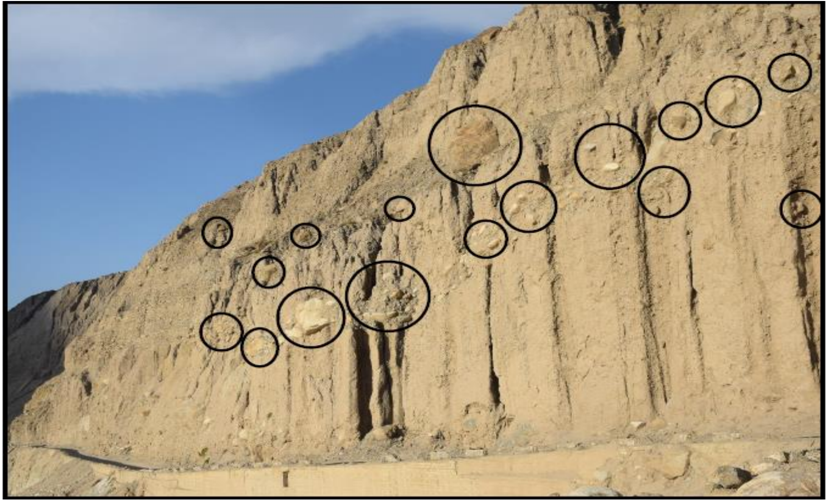


Figure VI (b): Aerial View of Tatta Pani area along KKH (Google earth).

7. Mitigation Strategies:

7.1 Early Warning Systems:

Among the numerous strategies for mitigating the risk to human life associated with landslides, early warning systems stand out as a substantial option for the authorities responsible for risk management and governance. (Luca Piciullo et al, 2018) The CPEC route in Gilgit Baltistan is crossing the Mighty Karakoram, Himalayas, and Hindu Kush mountain ranges, these mountainous terrains are more vulnerable to landslides due to slope failure and rock fall. The implementation of early warning systems in these regions serves as a vital tool for reducing disaster risk and minimizing the losses.

Landslide Early Warning Systems (LEWS) remain a challenge for researchers and practitioners. No universal system fits all situations; each LEWS must be designed to align with the specific landslide process, meet decision-makers' and end-users' expectations, and adhere to prevailing legal regulations. While LEWS can significantly reduce landslide-related fatalities, they are just one component of hazard mitigation strategies. The decision to install a LEWS involves weighing costs, benefits, and desired outcomes. The scale of forecasting (regional or local) influences technical approaches, with regional systems often relying on empirical rainfall thresholds, while local systems use complex slope monitoring and thresholds based on experience and expert judgment. (B.Thiebes, 2016).

7.2 Slope Stabilization Measures:

Landslides and issues related to slope stability, which initiate or intensify the displacement of soil masses, are notable geotechnical concerns and are recognized as substantial natural hazards. These hazards primarily arise from variations in strength at the interfaces of soil layers, such as soft soil overlying rock layers, as well as factors like heavy traffic loads, intense seasonal rainfall, and erosion at the base of slopes, rapid snowmelt, and other natural events. (Omer F. Usluogullari, 2015). Many techniques are practiced for slope stabilization, but the most cost effective and ecofriendly is the slope stabilization through slope revegetation. It is done through the planting of vegetation and adapting the construction method to stabilize barren slopes disrupted by road and building projects has been a common practice in the past decades. It remains the most environment-friendly and cost-effective technique for slope stability and environmental restoration performance in difficult regions. However, success is influenced by such factors as intense rainfall and steep slopes. However, the success of revegetated slopes can be compromised by various environmental factors, including intense rainfall and steep inclines. Numerous applications of slope revegetation aim to stabilize barren slopes resulting from urban development and road construction. Hydro seeding, in particular, has found widespread use on expansive and steep slopes in temperate climates. (Sung-Ho Kil et al, 2016). The Slope can be excavated mechanically to make it more stable in some area where there is clayey soil.

7.3 Policy and Planning Recommendations:

CPEC brings economic prospects to financially strapped Gilgit Baltistan but raises environmental concerns. The region, previously transformed by the Karakoram Highway, faces a critical juncture with potential development opportunities and ecological risks (Khalil, 2021). In regions like Gilgit Baltistan, the implementation of projects like CPEC requires pivotal government policies and planning to safeguard the environment and ensure safety from potential disasters. Recommendations include measures to mitigate the impacts of landslides along the CPEC route.

- Strictly implement policy measures outlined by NDMA and GBDMA for landslide-prone areas.
- Conduct extensive studies on soil profiling and develop new models to counteract landslide impacts.
- Prioritize tree planting, forest conservation, and minimize deforestation for environmental resilience.
- Exercise caution in construction activities, avoiding excessive blasting to prevent soil destabilization and reduce the risk of landslides.

8. Challenges and future research directions

8.1 Existing Challenges in Geotechnical Analysis:

Foremost, we need to address the challenge posed by the rising occurrences of slope failures and their escalating adverse impacts. These trends persist despite substantial advancements in our comprehension of natural processes and the successful development of experimental, analytical, and design tools. (R N. Chowdhury, 2010).Mostly, these landslides are caused by natural disasters like earthquake, heavy rainfall and wind storms, but we cannot neglect Human activates like Urbanization and deforestation, etc. So, there is big challenge for the disaster management authorities to predict these disasters and develop new method to counter these problems. In a region like Gilgit Baltistan which is not technologically advanced, this makes it very difficult to analyze and collect data with modern technological tools.

8.2 Recommendation for future researches:

The following recommendations are made for future research:

- Establish GIS and Soil Testing Labs in Gilgit Baltistan for local research.
- Use remote sensing tools to profile landslide-prone areas.
- Study soil characteristics of Karakoram, Himalayas, and Hindu Kush.
- Research vegetation for soil slope stabilization in mountainous regions.

9. Conclusion:

In conclusion, the geotechnical analysis of landslide events along the CPEC route in Gilgit Baltistan underscores the critical need to comprehend the intricate interplay of natural and anthropogenic factors influencing landslides. The region's diverse geological formations, seismic activity, and soil types render it susceptible to frequent landslides, exacerbated by factors like intense rainfall, snowmelt, and human activities, posing significant risks to infrastructure development.

The economic significance of the CPEC is acknowledged, yet environmental and societal challenges necessitate effective mitigation strategies. Case studies, such as the Attabad landslide and the Tatta Pani area, exemplify the region's vulnerability, emphasizing the urgency for robust mitigation measures.

Efforts to address the dangers of rock falls and landslides along the Karakoram Highway have been insufficient, largely due to the challenging terrain. The steep, unstable slopes and complex geology make implementing effective safety measures extremely difficult, requiring more advanced strategies and infrastructure than what is currently in place. Mitigation strategies, encompassing early warning systems and slope stabilization measures, are crucial for addressing landslide risks. Implementing Landslide Early Warning Systems (LEWS) stands out as a vital tool to reduce disaster risk and protect lives. Additionally, eco-friendly slope stabilization measures, including revegetation, are recommended to enhance slope stability.

Policy and planning recommendations are pivotal for the sustainable development of the CPEC route. Adherence to disaster management policies, extensive soil profiling, tree planting, and cautious construction practices are essential steps to mitigate landslide impacts and ensure environmental resilience.

Despite advancements in geotechnical analysis, challenges persist, particularly in technologically limited regions like Gilgit Baltistan. Future research should focus on overcoming these challenges, developing innovative disaster prediction methods, and leveraging modern technology to enhance the region's resilience to landslides and geohazards.

In summary, this research is a valuable resource for policymakers, researchers, and practitioners involved in critical infrastructure projects in landslide-prone regions. By integrating geotechnical analysis, case studies, and mitigation strategies, the study contributes to a holistic understanding of landslide events along the CPEC route in Gilgit Baltistan, laying the groundwork for sustainable and resilient development in the face of geohazards.

Conflicts of interest: There is no conflict of interest in this manuscript.

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