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ORIGINAL PAPER

Forensic investigation of roadside cut slope landslide in the lesser Himalayan region of Nepal

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Abstract
The failures in the roadside cut slopes in the Himalayan region are common events. However, the limited site-specific investigations often lead to reoccurring failures and escalating costs. This study attempts to critically examine a landslide along a national highway in Nepal's Lesser Himalayas using a forensic geotechnical approach, providing insights that can be applied to similar terrains around the world. Assisted with the desk works and site visits, geophysical investigations were carried out employing Electrical Resistivity Tomography (ERT) combined with geotechnical investigation, boreholes drilling for the subsurface inspection and interpretation. The data collected from these studies were used to conduct slope stability analysis using Limit Equilibrium Method (LEM) based numerical modeling. The analysis showed an alarming low factor of safety (0.791 on the hillside and 0.799 on the valley side), primarily due to high groundwater table on the sand-dominant slope. These findings highlight the necessity for effective groundwater management and slope reinforcement for the mitigation of instability. This study aims to improve slope stability assessments and disaster resilience in landslide-prone areas around the world by showcasing a comprehensive investigation approach.

Keywords Landslides · Geophysical · Geotechnical · Slope stability · Resistivity · Factor of safety · Seepage

1 Introduction

Landslides are complex natural events caused by the influence of numerous factors, both natural and human-induced (Bhandari and Dhakal 2021). Natural causes, such as seismic activity, rainfall, and hurricanes, play a significant role in triggering landslides (Alexander

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1992; Bai et al. 2020). These events may result from geological and geomorphological processes and occur globally (Cendrero and Dramis 1996; Conforti and Ietto 2021). Human activities like deforestation, overgrazing, and construction excavations also have considerable contributions to the occurrence of landslides. These hazardous events often arise from a complex interplay of socio-economic factors and substantially altered landscapes, where informal, non-engineered roads frequently fail during the monsoon every year (Gautam et al. 2021; Petley et al. 2007). While increased precipitation linked to climate change is frequently highlighted as a major cause, it is not the sole determinant (Bharti et al. 2016). For detailed comprehension of the landslide processes, it is necessary to study the geological (Bhandari and Dhakal 2018; Gerrard 1994; Hasegawa et al. 2009; Tsou et al. 2018), geotechnical (Tofani et al. 2017; Yalcin 2011), topographical (Tsou et al. 2018; Zhang et al. 2016), and hydrological (Dahal et al. 2008; Dahal and Hasegawa 2008) conditions of the affected area (Bhandari and Dhakal 2021).

The consequences of landslides extend far beyond the immediate physical changes of the affected area, severely impacting human life and the economy. They cause infrastructure damage, alter the topography, and negatively influence the socio-economic values of the affected area (Cendrero and Dramis 1996; Conforti et al. 2016; Conforti and Ietto 2019; Glade and Crozier 2005; Ietto et al. 2014; Klose et al. 2015). The deaths caused by landslides and debris flow comprise 17% of those caused by natural hazards (Herath and Wang 2009; Shahi et al. 2022). In the Himalayan region, a tectonically active region extending 2,400 km long, annual landslide damages alone account for over 1 billion US dollars, with hundreds of lives lost each year (Panthee et al. 2023). As a result, this value makes up around one-third of the global economic losses related to landslides (Dahal 2012; Li 1990). Colombia, Tajikistan, India, and Nepal are among the highest landslide susceptibility risk regions, with an estimated death toll of more than one per 100 km^2 (Nadim et al. 2006). Some incidents present even greater challenges in the Himalayas, such as the landslide of 1993 in Kulekhani watershed, induced by intense rainfall and claiming 1138 lives. Subsequently, more than 300 landslides were set in motion by the event within two days, flooding the downstream of the watershed and increasing the death toll to more than 1500 (Dhital 2003; Paudel et al. 2020). Another scenario worth noting is the recurring landslides, which are, in fact, simply due to untreated cases. The most striking example is the revival of Kotrupi landslide in 2017, which had already failed three times at an approximately 20-year periodic interval since 1977. It covered up nearly 300 m road strip of a national highway in Himachal Pradesh, India, sweeping the vehicles on the road, obstructing as far as a kilometer of downstream drainage and causing over 50 fatalities (Pandey et al. 2024). The persistent nature of landslide can also be observed in the Lesser Himalayas of Western Nepal. Diwakar et al. (2023) studied the frequent landslides and debris flow in Kalli village and noted the differential weathering of alternating shale and sandstone layers within the Suntar formation as a primary factor in these rainfall-triggered failures.

Nepal occupies an 800 km-long central part of the Himalayan region, experiencing significant seismic activity (KC et al. 2025; Subedi et al. 2025). The landslides and related disasters result in over 300 human deaths annually (Lamichhane and Bhattarai 2019; Shrestha et al. 2004). Despite the mountainous topography and failure-prone rugged and steep slopes covering approximately 83% of Nepal, a proper system to address the landslide-related events has yet to be established (KC et al. 2023). Efforts to identify landslide-prone areas have been inadequate, with the conducted landslide hazard mapping covering only a small area of the country (Bhandary et al. 2013; KC et al. 2024). Moreover, these natural slopes often undergo excavation during road construction to improve transportation and communication facilities. Over time, the geotechnical properties of slope materials change due to weathering and consequently the number of slope failure increases (Komadja et al. 2021; Miščević and Vlastelica 2014; Tran et al. 2019). The poorly constructed road areas are likely to experience double the monsoon-triggered landslides in comparison to the same areas without the road (McAdoo et al. 2018; KC et al. 2024).

In most cases of road designs and constructions in Nepal, there is a lack of consideration of roadside slope safety (KC et al. 2024). Additionally, even in the case of most highway maintenance studies, there has been a prioritized focus on pavement and bridge maintenance due to their high cost-nature and traffic-dependent sensitivity (Jha and Abdullah 2006; Pantha et al. 2010). However, the recurrent maintenance of the pavements due to slope failure makes it an absurd action and demands the consideration of the study of the failed and susceptible slopes. Though several studies have been done in the case of the landslides and failures in the roadside cut slopes in the Nepali Himalayan roads, the concept of forensic investigation is essential to be administered for complete resilience. In the context of disaster studies, the term "forensic" refers to the research of underlying causes, with the goal of determining the social dynamics, physical forces, and roles of institutional and social factors that contribute to risk factors. These characteristics influence susceptibility and exposure patterns, hence amplifying the impact of natural or manmade risks (Oliver-Smith 2016).

This study employs a forensic investigation approach to uncover the issue of landslides in the Midhill Highway, one of the major highways of Nepal, taking a case study of Inarpani landslide. The study intends to assess instability caused by groundwater, pinpoint important failure reasons, and suggest practical mitigation techniques for roadside slopes. A comprehensive study of the site has been done through rigorous field investigations and detailed results of the landslide along with the surrounding areas, the root mechanism, factors triggering it, and possible effective measures have been presented. These findings provide insights on the landslide unique to this research, underscoring the importance of conducting a similar site-specific study for each susceptible and failed zone for effective mitigation. This all-encompassing strategy fills up important information gaps and provides a framework for enhancing infrastructure design and disaster resilience in comparable geohazard-prone areas.

2 Study area

The Midhill Highway (also known as Pushpalal Highway), one of the national pride projects, will traverse through the central part of Nepal, from Panchathar in the east to Baitadi in the far west, spanning approximately 1,776 km upon completion (DOR 2011). The highway number is numbered NH03 and has been envisioned to facilitate easy and convenient access to around 7 million people from 24 hilly districts, allowing the underprivileged and economically stagnant communities to have easier access to the higher-level market areas (Gautam and Lal 2023; MOUD 2017). The slope failure investigated at Inarpani lies in the central region of the highway, as depicted in Fig. 1, positioned at 28°15'46"N, 83°30'48.36"E. Situated at an elevation of about 1564 m above mean sea level (masl), it covers an area totaling approximately 15,000 m^2. The area experiences a mean monthly precipitation of

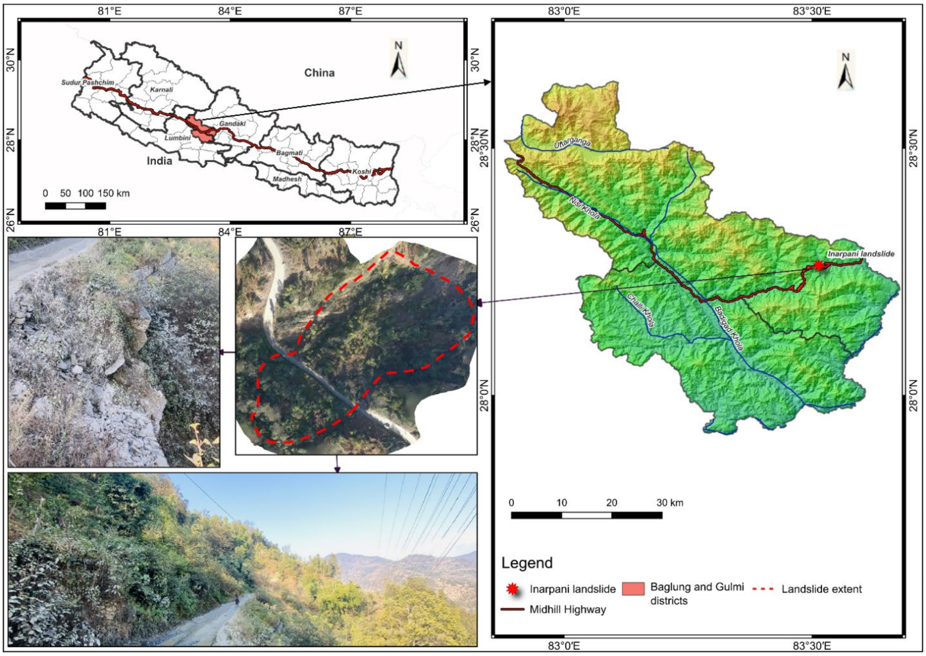

Fig. 1 Map of the study area showing its location, extent and condition

190.44 mm, as recorded by the stations in Baglung district spanning from 1970 to 2018 (Baral 2019).

Geologically, the studied area falls within the Lesser Himalayan zone, encompassing diverse rock types such as gneisses, migmatites, quartzites, phyllites, slates, and schists (Upreti 1999). This region of the Lesser Himalaya is characterized by notable tectonic structures such as folds, nappes, klippes, and schuppen structure, situated in close proximity to the Main Central Thrust (MCT), a major geological boundary in the Himalayas (Dhakal et al. 2019). High seismic activity of the region could potentially create fractures and structurally weak masses, serving as a region of colluvium generation. The slide area belongs to the Lakharpata subgroup within the Midland group, part of the Sangram formation, which consists of black, dark grey, and greenish-grey shales interspersed with layers of limestone and quartzite (DMG 2020). Colluvial deposits on the slopes, derived from weathering and disintegration of these mineral rocks, are highly susceptible to instability contingent on the rainfall intensity (Singh 2009).

This landslide can be categorized as a creeping type, which means it moves slowly downward, causing structural damage over time. On-site observations reveal more severe impacts on the slope. This movement has resulted in fissures in houses and damage to gabion walls on both the hillside and valley sides.

3 Material and method

The investigation of slope stability was carried out in three phases: inception, investigation, and analysis, as highlighted in Fig. 2. The inception phase involved mainly a desk to collect information about the site and the associated problems, followed by a reconnaissance survey and a drone survey to ensure proper inspection of the landslide area. During the investigation phase, an overall study of the site's lithology, geology, hydrology, and geotechnical properties was done. By combining hydrological, geotechnical, and geophysical data, this study uses a forensic framework to reconstruct the failure mechanism with an emphasis on causative attribution and evidence-based slope stabilization suggestions.

3.1 Geophysical investigation

This study employed Electrical Resistivity Tomography (ERT) survey for the geophysical investigation of the Inarpani landslide area. This conventional method was chosen due to its cost-effectiveness, rapid data collection, and ability to offer insights into shallow bedrock and overlying materials (Bogoslovsky and Ogilvy 1977; Donohue et al. 2012; Lundström et al. 2009; Malehmir et al. 2013).

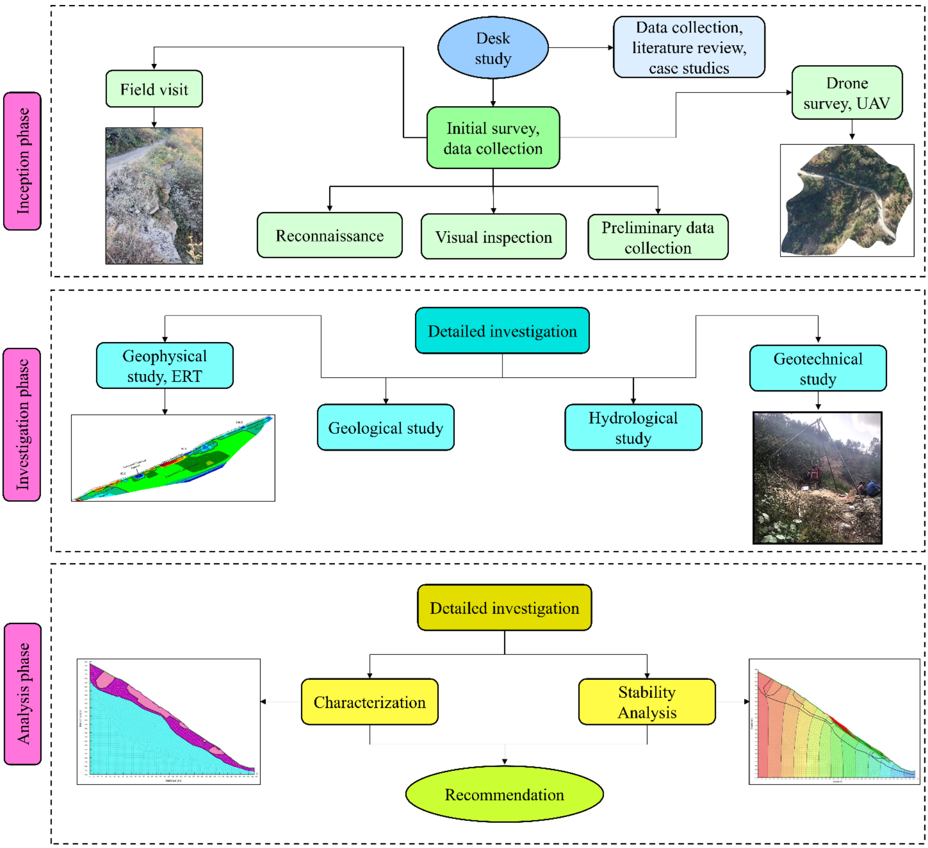

Fig. 2 Flowchart of detailed methodology of the slope stability study

For electrical resistivity profiling, a traditional electrode array, Wenner array configuration was selected due to its effectiveness in depth of investigation (Barker 1989), precision in horizontal and vertical detail (Barker 1979) and signal-to-noise ratio (Dahlin and Zhou 2004) as similarly noted by Martorana et al. (2017). To cover the landslide area, three 2D ERT profiles were surveyed as shown in Fig. 3: ERT-1 with a total spread of 360 m, employing 60 electrodes spaced 6 m apart; and ERT-2 and ERT-3, each with a total spread of 180 m, using 30 electrodes with the same spacing. ERT-1 extended from 28°15’44.47” N, 83°30’55.24”E to 28°15’48.48”N, 83°30’43.88”E, while ERT-2 and ERT-3 measured from 28°15’40.90”N, 83°30’51.95”E to 28°15’49.94”N, 83°30’49.77”E and from 28°15’42.39”N, 83°30’47.30”E to 28°15’45.82”N, 83°30’49.47”E, respectively.

The apparent resistivity of rocks, which reflects the combined effect of heterogeneous and complex anisotropic layers, was measured by a resistivity meter using the principles of Ohm’s law. Apparent resistivity values obtained in the field differ from the actual resistivity of geological units unless measurements are taken over homogeneous ground (Telford et al. 1990). Consequently, the field data were processed using RES2DINV software, which inverts the data to generate true resistivity contours for lithological and geological interpretation. The geology of the site was considered for the interpretation since different lithological conditions can give similar resistivity values. Based on the studies ofLaBrecque and Ward (1990) and Palacky (1987), different values of resistivity were considered, and ranges were deduced to delineate the lithology of the site in compliance with the geology of the area, as shown in Fig. 4.

3.2 Geotechnical investigation

To achieve a comprehensive interpretation and analyze the correlation between the lithology of the landslides and the determined distribution of electrical resistivity along the profile, the geotechnical investigation work was conducted in accordance with the IS 1892:1979. For this purpose, two boreholes of 20 m were dug out in such locations that would represent

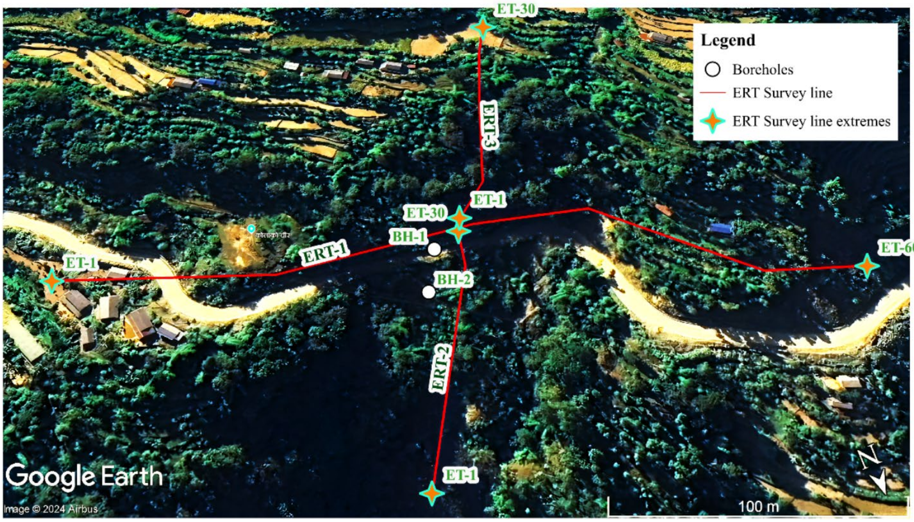

Fig. 3 Google earth image showing the layouts of the ERT profiles and borehole location

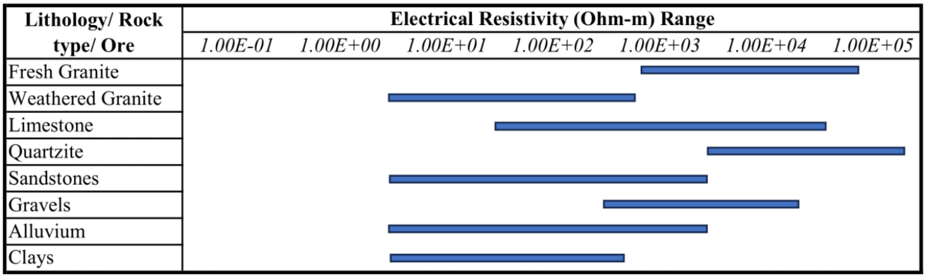

Fig. 4 Resistivity ranges for some common type of minerals found in Lesser Himalayas

the entire study area and undisturbed soil samples were collected at intervals of 1 m along depths up to 5 m for first borehole (BH-1) and up to 10 m for second borehole (BH-2). The coordinates of BH-1 and BH-2 are 28°15’45.960"N, 83°30’49.719"E and 28°15’46.449"N, 83°30’50.016"E respectively. The tests were carried out in two steps: laboratory tests and field tests.

3.2.1 Field tests

Dynamic Cone Penetration Tests (DCPT) were carried out up to the depth of 20 m as per IS 4968: Part III (1976). In accordance with typical geotechnical practice, groundwater levels were measured 24 h after the completion of the borehole to allow for stabilization. In order to deduce groundwater changes, field observations of seepage zones, neighboring springs, and water buildup patterns were also recorded.

Field observations of water seepage were combined with historical rainfall data from nearby weather stations to estimate monsoon groundwater conditions. Additional information about seasonal variations was revealed by the existence of perched water tables and saturation levels in borehole logs. A more thorough knowledge of groundwater’s role in landslide was ensured by including these data into the SEEP/W study, which simulated groundwater behavior during peak monsoon times. The disturbed samples were collected for further tests in the laboratory following the Indian Standards.

3.2.2 Laboratory tests

To determine the soil properties and understand the material composition contributing to landslide, sieve analysis, natural moisture content, bulk density, specific gravity and direct shear test (DST) were conducted in the laboratory following IS 2720: Part IV (1985), IS 2720: Part II (1973), IS 2720: Part III (1980), and IS 2720: Part XIII (1986), respectively. The number of these tests were mainly dependent upon the type of formation encountered in the boreholes.

3.3 Slope stability analysis

The natural terrain profile after the failure was considered for the analysis by defining the subsoil layers based on the findings from both geophysical and geotechnical investigations. The water table condition during the monsoon period was estimated based on the present water table recorded from field observations, springs and seepage levels, as well as the saturation layer observed from geophysical tests.

The slope stability analysis was done using GEOSTUDIO software as illustrated in Fig. 5. The most critical section was selected after field works such as finalization of level of existing landslide crown, road level and the toe area of landslide and desk works such as topographical survey, geophysical testing and geotechnical investigations. This approach ensured the accuracy of the derived geometrical setup for modelling to represent the real-world conditions of the site. Two strategically placed boreholes adequately covered the slope's lithology as confirmed by the consistency of the subsurface conditions stemmed from the conducted geophysical study. GEOSTUDIO modules SEEP/W and SLOPE/W were employed for a comprehensive analysis of the slope. The input parameters for the simplified model of the critical section were deduced from the soil properties as obtained from geotechnical tests and confirmed by the ERT profiles. SEEP/W was utilized to simulate the movement of water through saturated and unsaturated porous media, while SLOPE/W was used for static or pseudo-dynamic slope stability analysis. The SLOPE/W analysis uses Limit Equilibrium Method (LEM) for soil masses, as in our case and Finite Element Method (FEM) for rock slopes, while SEEP/W exclusively employs FEM. In SEEP/W, the water level was defined along the top of the saturated layer as interpreted from the ERT, with entry and exit points verified in the field. SLOPE/W, based on the limit equilibrium method, offered essential insights into the slope stability by calculating factor of safety (FOS) of the slope (Paul et al. 2022). In this analysis, shear strength parameters (cohesion and friction angle) and unit weights were simply inferred from the test data for the suitability of the section. The boundary conditions in SEEP/W are as follows: an impervious condition is assigned at the bottom boundary, a potential seepage face is specified on the slope face at the location where seepage discharge is observed, and a water head is applied above the current water table on the left boundary. Generally, a slope with FOS less than 1 is considered to be unstable. However, a safety factor of 1.3 or higher is preferred for determining slope stability, as it accounts for the potential uncertainties that can arise during laboratory testing (Stark and Ruffing 2017). Consequently, in this study, a slope is considered stable only if its safety factor exceeds 1.3, reflecting the uncertainties that may emerge throughout the entire process.

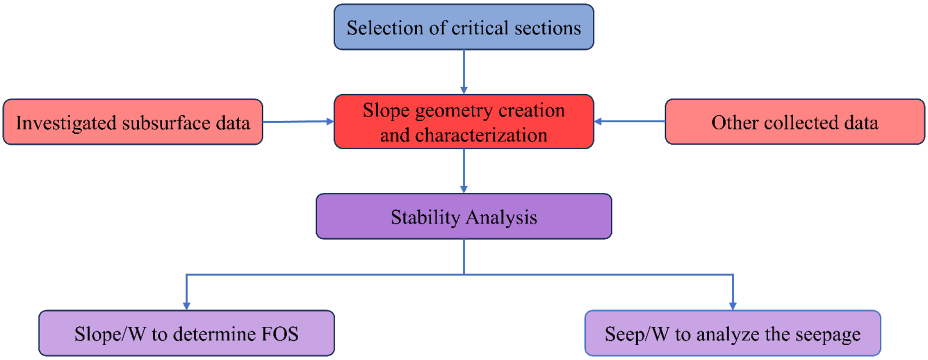

Fig. 5 Flowchart illustrating the steps involved in the analysis of slope stability using GEOSTUDIO

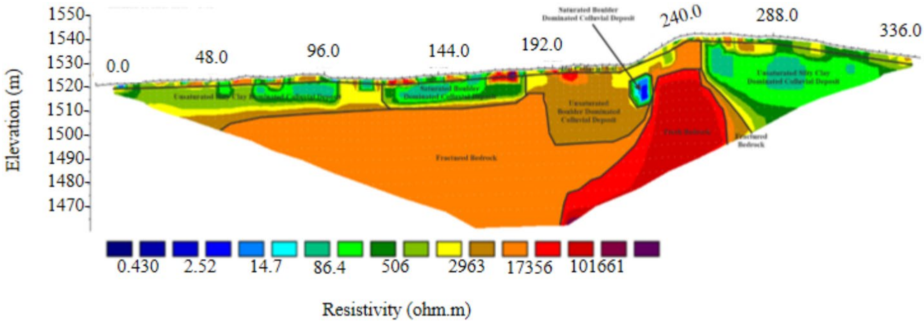

Fig. 6 ERT-1 profile inversion result and interpreted lithology showing different soil layers: colluvial deposits overlying the fractured bedrock

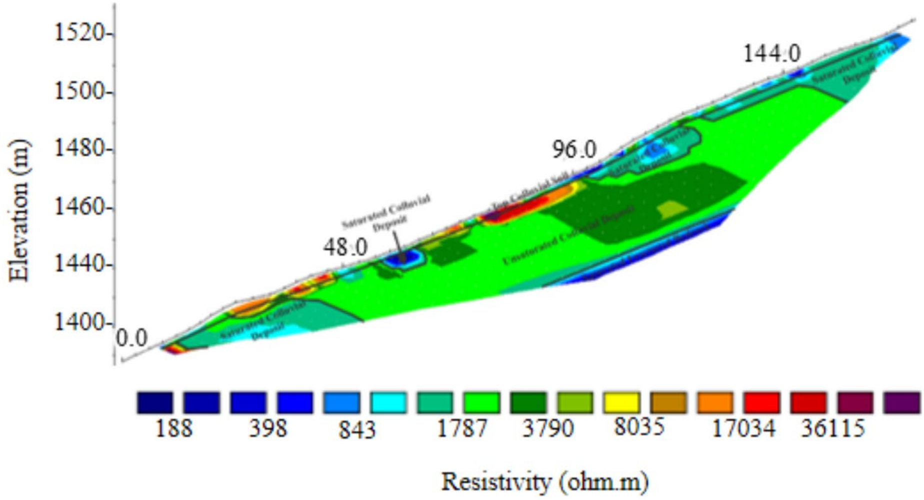

Fig. 7 ERT-2 profile inversion result and interpreted lithology showing different soil layers: colluvial deposits overlying the saturated fractured bedrock

4 Results

4.1 Geophysical investigation

The ERT surveys detected varying subsurface materials, from colluvial soil to saturated deposits and fractured bedrock as illustrated in Figs. 6, 7, and 8. Low resistivity zones indicated high moisture content and potential weaknesses which could have induced the slope instability.

4.1.1 ERT-1 profile

The 360 m long ERT-1 profile revealed various distinct resistivity zones. Near the surface, 2 to 5 m thick, organic colluvial soil was observed, with low resistivity patches indicating silty

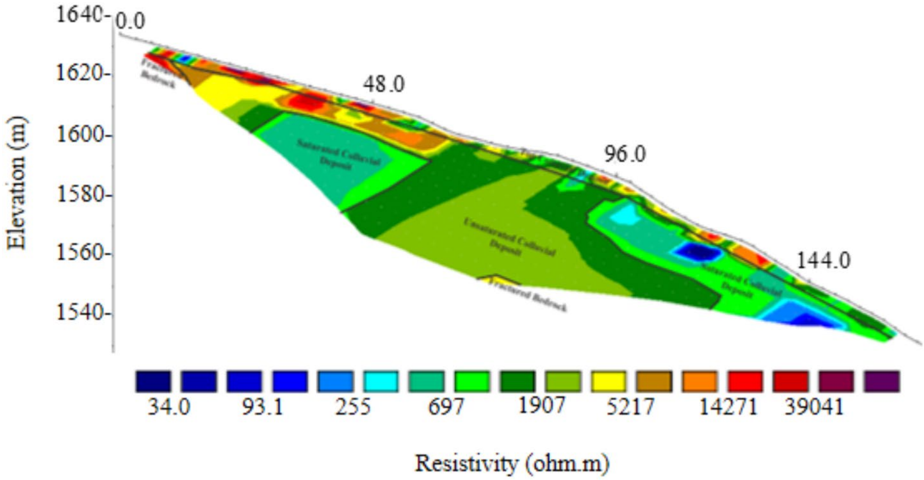

Fig. 8 ERT-3 profile inversion result and interpreted lithology showing different soil layers: saturated and unsaturated colluvial deposits

clay and higher resistivity patches indicating gravelly materials. Below this, a low to moderate resistive contour suggested a range of 10–30 m thick colluvial layers such as unsaturated clay-dominated colluvial soil, saturated boulder-dominated deposits, unsaturated boulder dominated colluvial soil and unsaturated silty clay dominated colluvial deposit along the cable profile (Fig. 6). Underneath the colluvial layer up to the investigation depth, higher resistivity contours were encountered, which could be expected to be the fresh or fractured bed rocks consisting of thin to medium grained fractured and weathered carbonaceous shale.

4.1.2 ERT-2 profile

The 180 m long ERT-2 profile exhibited patterns similar to those of ERT-1. In the upper 2 to 5 m, colluvial soil contained silty clay (low resistivity) and gravelly materials (high resistivity). Below this layer, a zone with low to moderate resistivity suggested the existence of saturated colluvial deposit up to the investigation depth and moderate to high resistivity indicated 20–30 m thick unsaturated colluvial deposit (Fig. 7). Because of the presence of highly fractured and weathered carbonaceous shale, saturated fractured bedrock below the unsaturated colluvial deposit, had very low resistivity.

4.1.3 ERT-3 profile

The ERT-3 profile, spanning 180 m, identified top layers of organic colluvial soil (2 to 5 m thick) with low resistivity patches representing the silty clay dominated area and high resistivity patches, the weathered and fractured rock. A high resistivity zone from chainage 9 to 99 m indicated unsaturated colluvial deposit underlain by medium resistivity (saturated colluvial soil) and moderate resistivity (fractured bedrock) in different sections (Fig. 8). The latter chainage part encountered 10 m thick lower resistivity contour, suggesting saturated colluvial deposit. The angular fragments of shale were the clast and matrix of the soil.

In chainage 84, fractured bedrock was detected after interpreting the moderate resistivity contour.

4.2 Geotechnical investigation

4.2.1 Field tests

The DCPT results were converted into correlated SPT N-values which provided additional insights into the subsurface conditions, with high penetration resistance values (N-values), indicating medium to very dense soil layers. Specifically, N-values increased to 50 just after 4.5 m and 3 m depths in BH-1 and BH-2, respectively indicating abrupt change in the subsurface lithology as depicted in Fig. 9. These findings confirm the competent nature of the subsurface layer to bear loads and sustain stability. However, the groundwater table was observed to be at about 1 m in both boreholes. The presence of water table at this shallow depth could be the potential reason for the weakness of the slope.

4.2.2 Laboratory tests

The laboratory test results are presented in Table 1. Sieve analysis of soil samples from two boreholes revealed notable compositional variations. Soil samples from two boreholes indicated distinct compositional variations. BH-1 was primarily sandy, with sand content between 85.17% and 93.73% and minor variability in gravel, clay, and silt. However, at 7.5 m depth, gravel and fines were notably higher at 23.06% and 10.15%, respectively. In contrast, BH-2 had lower sand content (50.59–66.33%), higher gravel content (28.72–

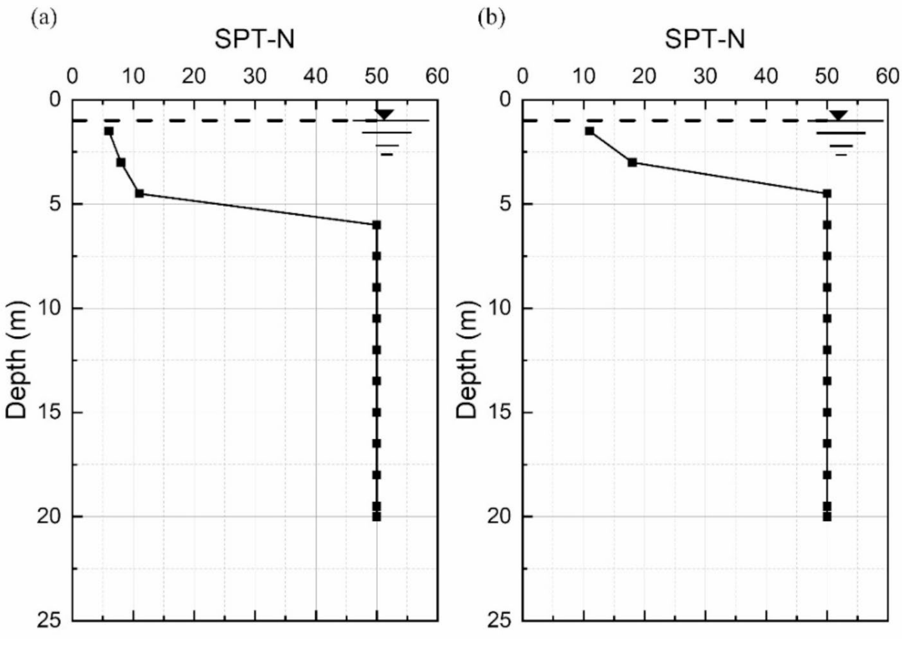

Fig. 9 Borehole logs showing SPT N-values and groundwater level of (**a**) BH-1 and (**b**) BH-2

42.98%), and fines ranging from 4.55 to 7.76%. These variations indicate a complex, heterogeneous subsurface in the study area. Also, plotting these data with liquefaction range suggested by (Tsuchida and Hayashi 1972) as illustrated in Fig. 10, indicates a modest level of susceptibility to liquefaction. Since, cohesionless sands are deemed susceptible to liquefaction and the sand contents in this region are found to be high, the failure can also be triggered during earthquake.

Natural moisture content (NMC) was measured across different depths. In BH-1, moisture content increased from 10.19 to 55.76% up to a depth of 7.5 m, followed by a decline. This trend is likely due to the soil composition, as higher clay and lower sand content enhance water retention. On the other hand, NMC in BH-2 ranged from 8.52 to 15.26%, with higher values near the surface. Higher moisture in the upper layers suggests more weathering and surface water infiltration. These high values of NMC at shallow depths also signify high ground water table in the site.

Specific gravity values for both boreholes ranged from 2.66 to 2.72, typical for sandy and gravelly soils, reflecting similar mineral composition across the site. Direct Shear Test results revealed an angle of internal friction (φ) between 27° and 32° and cohesion (c) between 9.19 and 15.79 kN/m², indicating moderate to high shear strength. However, higher moisture of the sample in the deeper samples constrained the consideration for the tests only up to 5 m in BH-1 and 4 m in BH-2.

4.3 Slope stability analysis

The geotechnical investigations at the site (Fig. 11 (a)) have identified several critical concerns affecting both the hill and valley sides of the highway. SEEP/W analysis highlighted numerous seepage pockets, with groundwater levels nearly reaching the surface as illustrated in Fig. 11 (b), while SLOPE/W analysis revealed alarmingly low FOS of 0.791 on the hill side and 0.799 on the valley side as depicted in Fig. 12. The primary cause of the low FOS is excessive seepage, which exacerbates slope instability and heightens the risk of

Table 1 General summary of the properties of soils from landslide-affected area

Borehole	Depth (m)	NMC (%)	Bulk Density (gm/cc)	Specific Gravity	Direct Shear	
					φ (°)	c(kN/m²)
BH-1	0.0–1.0	10.19	1.88	2.68	30	12.92
	1.0–2.0	10.87	1.88	2.68	31	12.63
	2.0–3.0	12.24	1.91	2.67	32	9.19
	3.0–4.0	16.61	1.99	2.64	32	12.06
	4.0–5.0	18.70	1.98	2.68	32	13.49
	5.0-5.2	19.93	2.02	2.70	–	–
	6.0-6.2	26.97	1.94	2.70	–	–
	7.5	55.76	2.39	2.66	–	–
	8.0	24.18	1.89	2.72	–	–
	9.0–10.0	23.88	2.03	2.68	–	–
BH-2	0.0–1.0	15.26	1.84	2.67	29	15.79
	1.0–2.0	20.12	1.84	2.65	27	15.79
	2.0–3.0	9.20	1.70	2.67	29	12.06
	3.0–4.0	12.85	1.73	2.68	28	13.78
	4.0–5.0	8.52	1.65	2.69	–	–

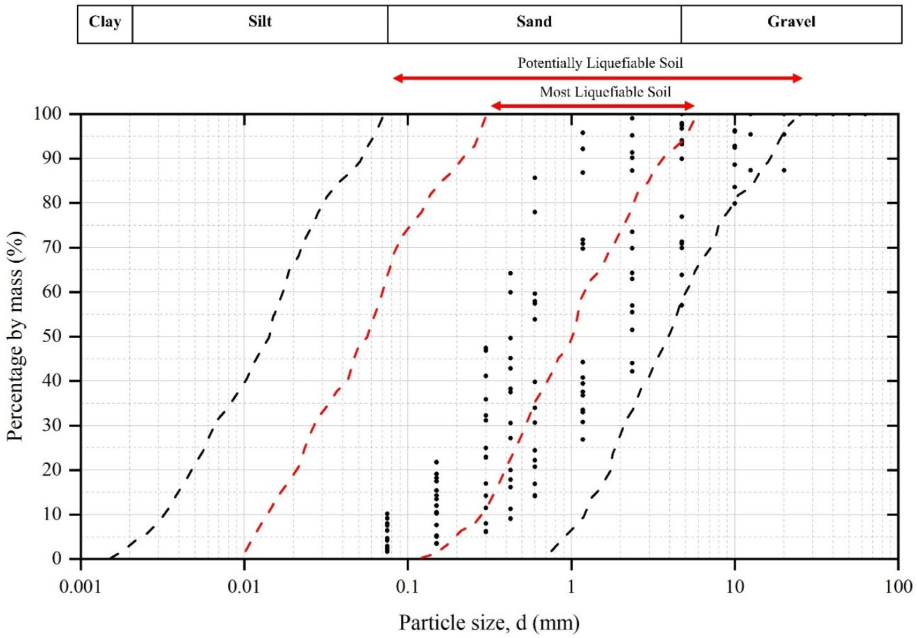

Fig. 10 Particle size distribution graph of the site soils from BH-1 and BH-2 at different depths with a demarcation of liquefiable soils suggested by Tsuchida and Hayashi (1972)

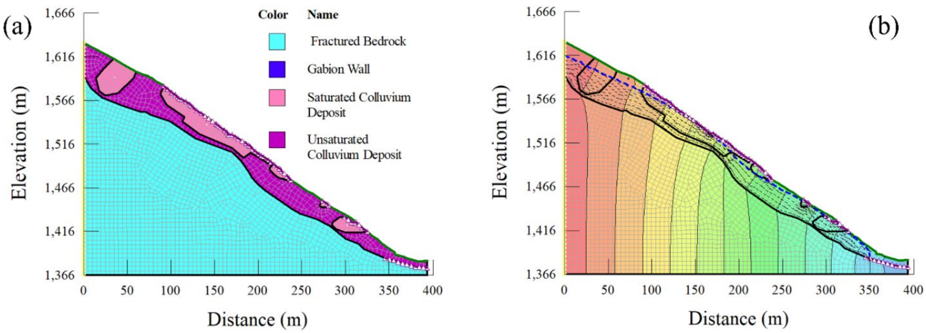

Fig. 11 (**a**) Interpreted GEOSTUDIO model of the critical section, (**b**) SEEP/W output under existing condition showing Seepage pockets and groundwater level

landslides. The hill side is particularly unstable because of a thick colluvium deposit that is prone to shifting. Additionally, deep-seated failure driven by subsurface moisture contributes to instability at greater depths, leading to significant earth movement. Tension cracks observed near the crown and sides of the slide indicate ongoing stress and the potential for further displacement, threatening infrastructure and nearby settlements (Carlà et al. 2018). These findings reflect a typical scenario of slope failure in Nepalese Himalaya, where high water tables and tension cracks are widespread occurrence in response to monsoon rainfall in the precarious steep landscapes. The aforementioned factors collectively pose serious

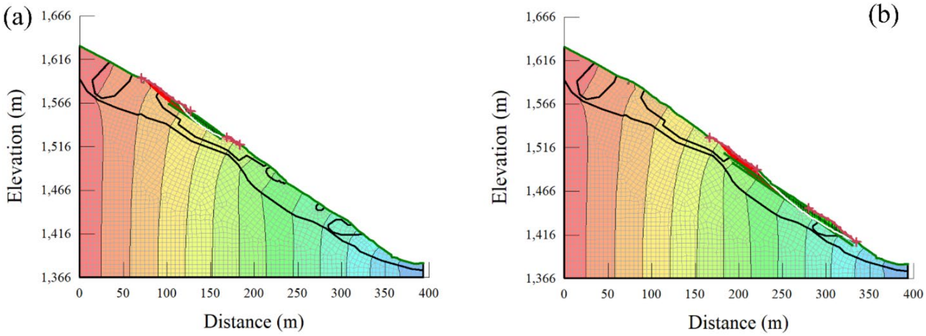

Fig. 12 SLOPE/W Output under existing conditions: (**a**) SLOPE/W output indicating possible slip surface on hillside with FOS = 0.791, (**b**) SLOPE/W output indicating possible slip surface on valley side with FOS = 0.799

safety hazards for highway travelers and area residents, risking erosion and road damage, thereby impacting transportation and connectivity. Therefore, it is necessary to incorporate proper mitigation strategies to slope failures in infrastructure development planning.

This study emphasizes the necessity of enhanced drainage management, strengthened retaining structures, and bioengineering methods in Nepal to improve slope stability practices. Early failure risk identification can be facilitated by requiring geotechnical and geophysical studies prior to road-cut excavations. Since present recommendations frequently ignore these crucial assessments, which can result in expensive failures, policy improvements should incorporate slope stability studies into infrastructure development. Furthermore, funding engineering and planning capacity-building initiatives can improve disaster resilience and lower the long-term financial and human costs of landslides.

Since the analysis indicates subsurface water as the primary cause for the failure of the slope, the stability can be greatly increased by managing it with the use of subsurface drains. The weak colluvial deposits on the hillside can be supported by simply installing gabion walls reinforced with anchors. Additionally, bioengineering techniques can be introduced to the whole slope to increase sustainability. For the reanalysis, the subsurface drains were strategically placed at each seepage pockets resulting in significant lowering of groundwater table, while additional support on the roadside with gabion walls boosted the FOS to above 1.3 as per safety requirement. These measures, especially bioengineering, using suitable vegetation, are sustainable and economical strategies for a country grappling with environmental and economic adversity like Nepal. Furthermore, tools like SLOPE/W and SEEP/W, in conjunction with geophysical and geotechnical studies, can help identify the problem as well as validate the effectiveness of the chosen mitigation, significantly enhancing slope stability practices.

5 Discussion

A landslide can exhibit different types of movement such as fall, topple, slide, lateral spread, flow and even complex movement (Varnes 1978). The Inarpani landslide, situated on a roadside cut slope in the Lesser Himalayas of Nepal, exhibits creeping characteristics as revealed by the investigations. The colluvial soils with high sand and moisture content, found at the site, pose significant stability challenges. Unlike large-scale landslides linked to hydrothermal alteration and clay mineralization due to the advancement of MCT, as discussed by Hasegawa et al. (2009) in central Nepal, no clay mineralization zone was detected in our investigation. However, this was reflected from the general interpretation of ERT and geotechnical analysis of two boreholes rather than specific focus on observing such zone in the study area. This deviation suggests that other factors are at play, particularly related to road construction practices. Consistent with the findings of Dhungana and Maharjan (2023) from the Pokhara-Baglung Highway, poor bedrock excavation management and ineffective drainage systems significantly contribute to slope failures. Sati et al. (2011) pointed out that improper consideration of geology during road alignment and faulty engineering techniques are key contributors to landslides in Uttarakhand. These findings align with the Inarpani case, where inadequate slope safety considerations during road excavation have led to landslide.

The triggering factor for the gradual failure in Inarpani slope has been identified as a high groundwater table exacerbated by rainfall. As opposed to earthquake-induced landslides that typically affect convex slopes, most rainfall-induced landslides occur on concave slopes (Parkash 2013). Furthermore, the forensic analysis of the Malin landslide by Ering et al. (2015) explained that heavy rainfall infiltration reduces suction strength at the interface of bedrock and soil, causing slope failure. While this mechanism could have contributed to the Inarpani failure, in this case, the failure did not initiate at the interface, but the water infiltration likely played a significant role. The water table, irrespective of its formation before or after the commencement of rainfall creates positive pore water pressure, reducing effective stress, thus, lowering the shear strength and consequently failure along the slip surface (Gasmo et al. 2000; Godt et al. 2009; Johnson and Sitar 1990; Kluger et al. 2020; Li et al. 2013; Ng and Shi 1998; Rahardjo et al. 2010). Presence of highly permeable material, overlying the less permeable one can cause rapid slope response to rainfall, potentially enough to suffice single rainfall to trigger the failure (Troncone et al. 2022). However, the study by Rahimi et al. (2010) stated that the stability depends on the intensity of the rainfall as higher rainfall intensities affect good drainage slopes and lower intensities aggravate the poor drainage soil slopes. In either case, managing the water properly can significantly increase the stability. Therefore, effective mitigation should focus on lowering the groundwater table through subsurface drains, reinforcing the slope with gabion walls and anchors as needed, and bioengineering the slope to enhance long-term stability. Particularly in the Himalayas, Andes, and other tectonically active mountainous regions, the results of this study can be applied to other areas with comparable geomorphological characteristics. Landslides caused by excessive groundwater levels and inadequate drainage systems have been well recorded in areas like China's Sichuan province and India's Western Ghats. In regions where instability brought on by rainfall is a frequent danger, the forensic methodology employed in this work can be utilized as a guide to comprehend slope failures. To increase road resilience in landslide-prone areas, planners and engineers can create region-specific mitigation measures by using a thorough investigative framework that combines geophysical, geotechnical, and numerical modeling techniques.

6 Conclusion

A comprehensive investigation was conducted to address the significant issue of roadside slope disaster at Inarpani along the Baglung-Burtibang road on the Midhill Highway in Baglung, where the landslide posed severe risks to infrastructure and public safety. The site investigation identified the study landslide as of the creeping type. Three ERT profiles showed the presence of low resistivity zones, indicating the possible weaknesses and high moisture content. The geotechnical investigation with the help of two boreholes revealed high moisture content with high ground water table at about 1 m, sandy soil, with minor gravel content. Even though the strength parameters were found to be moderate to high, such soil composition in the steep topography increases the susceptibility of collapse. This was backed by the SLOPE/W analysis in GEOSTUDIO revealing alarmingly low safety factors of 0.791 on the hillside and 0.799 on the valley side of the road. SEEP/W analysis further indicated high seepage and water level, supporting it to be the primary cause of the failure.

Despite rigorous methodology, this study has inherent limitations. The limited number of boreholes, due to cost constraints, may not fully represent the entire slope's variability. Additionally, while ERT provided valuable insights, its inherent limitations may have introduced minor errors in the model interpretation for analysis purposes. Due to advancement in the subsurface imaging, the lithological interpretation can be improvised by using cutting-edge technologies like 3D-ERT, Distributed Acoustic Sensing (DAS), Ground Penetrating Radar (GPR), seismic imaging and electromagnetic imaging. These technologies produce higher resolution imaging and could be used for corroboration by employing them in conjunction. Moreover, we employed a simplified model of the critical slope in GEOSTUDIO for SLOPE/W, and SEEP/W analysis; however, the results can be further compared with other modelling software. More extensive sampling and advanced modeling techniques should be considered for future research to improve the prediction of slope behavior. Nevertheless, resource constraints of our study limited the application of the referenced techniques and technologies.

This study has identified major contributing factors to the landslide at Inarpani. To solve these issues, subsurface drains, gabion walls reinforced with anchors, and bioengineering could be recommended. While this study focused on one site, slope failure is widespread issue across Nepal. By identifying the causes in similar or more advanced manner and addressing the critical issues at each possible unstable slopes, Nepal can substantially increase the safety and resilience of its roads and associated infrastructures and human lives in the mountainous regions.

The findings of the research are relevant not only for Nepal but also for mountainous areas across the world that experience comparable geohazards because of high-relief terrain, shifting lithology, and seasonal precipitation. The forensic geotechnical approach used in this work can be advantageous for nations like India, China, Japan, Colombia, and Peru where landslides along roadways provide ongoing threats. Slope failures can be evaluated and mitigated globally using a reproducible approach that combines geophysical surveys, borehole investigations, and numerical modeling. The report also emphasizes the urgent need for policy changes, calling for more stringent geotechnical assessments in road construction projects—not just in Nepal but also in other developing countries where infrastructure development frequently surpasses geohazard assessments.

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Data availability Data will be made available on request.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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