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Dynamics of active landslide along central Himalayan route: A case study of Guthitar landslide, Dhankuta, Nepal

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ABSTRACT

Landslides in the Nepal Himalayas are a common phenomenon because of the coupling effect of seismo-tectonic activities and the Asian Monsoon. Understanding landslides in this complex environment, particularly the behavior of active large landslides, is vital for sustainable infrastructure development. This study conducted comprehensive slope investigations, including geological, geophysical, and geotechnical investigation, along with instrumentation using inclinometers and a raingauge station, to identify the causes and mechanisms of failure at the active landslide slope at Guthitar on the Dharan-Dhankuta road. This landslide is active since 1987 but the movement has intensified from 2020 onwards. The detailed investigation reveals that the landslide exhibits multiple shallow-seated and deep-seated failure surfaces, some of which extend to the ground. Slope stability was modeled and analyzed using the Limit Equilibrium and Strength Reduction Methods. The results indicate multiple slip surfaces, with some discrepancies compared to field investigations, underscoring the limitations of numerical methods and the critical role of field monitoring systems. Furthermore, a comparison of rainfall data with deformation patterns from slope monitoring clearly demonstrates that prolonged rainfall increases the rate of movement by threefold. Thus, continuous landslide monitoring is essential to understand the mechanisms and triggers, enabling the implementation of effective landslide management strategies in the Himalayas.

Keywords: Geophysical Method; Himalaya; Landslide; Monitoring; Numerical Modelling

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INTRODUCTION

Background

Geo-hazards, particularly landslides, are among the principal challenges to road sustainability in the Nepal Himalayas (Hearn and Shakya, 2017; Paudyal et al., 2023). Landslides in this region are common, primarily due to the combined effects of seismo-tectonic activities and monsoon rainfall (Dahal, 2012; Pyakurel et al., 2023). These landslides range from shallow-seated to deep-seated, and from dormant to active states. A thorough understanding of the complex mechanisms and triggers of active deep-seated landslides (DSL) is crucial, as even minor initial movements can escalate into significant displacement and severe damage over time (Fosalau et al., 2015), underscoring the importance of sustainability and safety for transport infrastructure. Despite their significance, few studies have focused on quantifying and understanding deep-seated and large-scale landslides in the Nepal Himalayas. For example, Timilsina (2014) conducted morphometric mapping and analysis to determine the probability function of large-scale landslide distribution in the Lesser Himalayas (Timilsina et al., 2014). A similar study in western Nepal used a threshold depth of 10 m to differentiate between shallow and DSL. The results indicated that shallow-seated landslides strongly correlate with climatic factors, whereas DSL exhibit much lower correlation values, likely due to their distinct hydrological characteristics (Muñoz-Torrero Manchado et al., 2021). However, these studies overlook the varied dynamics of DSL. Globally, research into the mechanisms of DSL has shown that their depths can vary significantly, ranging from 10 m to over 250 m. These landslides can involve different types of movement, such as low-strain creep, which results from the ductile behavior of geomaterials under high confining stress (Dahal et al., 2019; Petley and Allison, 1997). An example is the Buonalbergo landslides, where small and consistent deformation rates occur under gravitational loads (Guerriero et al., 2021). Some landslides, like the Slumgullion landslide in the San Juan Mountains of Colorado, exhibit continuous deformation and have been actively moving for at least last 300 yr (Wang et al., 2018). In contrast, others, such as the Jure landslide in 2014, behave more like avalanches, with a volume of 5.05×10^6 m^3 (Panthee et al., 2023). The literature widely agrees that DSL are pivotal in shaping the morphology of landscapes, especially in areas where tectonic movements and river processes intensify these effects. For instance, parts of the lesser Himalaya uplift by 10 mm annually, while drainage incision rates range from 10-15 mm per year (Fort, 2011; Lavé and Avouac, 2001), highlighting the role of relative relief changes in regional instability.

DSL are often affected by human activities (Dille et al., 2022), but unlike shallow landslides, they do not show a strong correlation with climatic conditions and other geomorphological factors (Gariano and Guzzetti, 2016; Muñoz-Torrero Manchado et al., 2021; Panthee et al., 2023; Timilsina et al., 2014). Moreover, they cannot be predicted through regional studies and do not follow the same patterns. Therefore, DSL should be treated as unique phenomena, requiring proper investigation as well as analysis, and monitoring to gain a comprehensive understanding of their dynamics.

Road and landslide

Landslides occurring within road right-of-ways are commonly reported and can have significant consequences. For instance, the Krishna Bhir landslide, had a severe impact on connectivity and transport economy (Maskey, 2016) of Nepal. Similarly, many landslides are reported annually on the other highway sections such as the Mugling-Narayanghat road, Araniko Highway, and Karnali Highway during the monsoon season (Thapa, 2023). Additionally, some road sections suffer from long-term, deep-seated, and gradual large-scale landslides, like the Kothe landslide of Araniko Highway and Guthitar landslide of the Dharan-Dhankuta road on the Koshi Highway. The road section in Guthitar has experienced subsidence since 1987 due to continuous slope movement (Hearn and Martin, 2022). The Official Development Assistance (ODA, UK) or Department for International Development (DFID, UK) and later the Department of Roads (DoR, Nepal) have studied and implemented mitigation works in this section. Some works carried out during the period were reported in different literature (Hearn, 2002; Hearn and Martin, 2022; Martin, 2001). Martin (2001) focused on mitigating different earthquake induced instabilities within the first 26 km of the road from Dharan. A review of 25 yr of road construction in the Himalayas highlighted the mass movement at Guthitar since 1981 and the increased subsidence rate since 1987 (Hearn and Martin, 2022). Recently, there has been increased movement and instability after 2020 intense rainfall (Hearn and Martin, 2022), this chronic unstable section requires thorough investigation, monitoring, and analysis to design effective mitigation measures. The investigation process typically involves various field studies, tests, and monitoring of slope movements using inclinometers or extensometers, along with measuring other factors like groundwater levels and rainfall, which provide direct information about mass movement (Ausilio and Zimmaro, 2017).

Stability analysis and monitoring

The initial step in studying landslides and implementing appropriate mitigation measures involves slope assessment. This method is suitable for simple and straightforward cases. For more complex situations, detailed investigations followed by slope stability analysis are necessary. There are different approaches used for slope stability analysis, the foremost being the Limit Equilibrium Method (LEM). LEM calculates the factor of safety over a trial slip surface of the given slope, primarily using methods of slices. Originally based on engineering intuition, slice techniques gained widespread acceptance in the 1950s and 1960s as rigorous mechanical principles were developed, leading to the analysis and summarization of different limit equilibrium slice methods (Bishop, 1955; Fellenius, 1936; Janbu, 1954; Morgenstern and Price, 1965; Spencer, 1967). The second approach, the Strength Reduction Method (SRM), was developed in the 1990s (Swan et al., 1999; Zou et al., 1995) that reduces strength parameters in elastic-plastic finite element analysis until slope failure occurs, and its main advantage is the absence of a need for a predefined slip surface. However, it requires more geotechnical parameters, such as the modulus of elasticity and Poisson's ratio, and other parameters based on the selected constitutive models. Both LEM and SRM are used to evaluate the slopes in the region, but LEM is more common due to its simplicity and the accuracy in outcomes (Dhakal, 2019; Dhakal et al., 2019; Paudyal et al., 2023; Raj and Prasad, 2021; Robson et al., 2022).

Due to their nature and extent, some landslides require extensive work to be mitigated completely, or to understand the mechanisms of landslide movement, landslide monitoring is crucial. Geomorphological monitoring and warning systems have been reported since long ago (Guzzetti et al., 1999). Similarly, some studies have been reported in the Nepal Himalayas that involve monitoring systems developed through geomorphological analysis (Thapa et al., 2023; Thapa and Adhikari, 2019). These systems often lack site-specific geotechnical analysis of the slope and tend to fail after a few years (NDRRMA and NRA, 2021). A remote sensing based monitoring of slope deformation has been carried out in the Trishuli River basin and found effective in the monitoring of steep terrain (Bekaert et al., 2020). Additionally, low-cost, community-based slope monitoring systems are implemented in rural Nepal by various development partners and local governments, yet many remain unreported (Shrestha, 2017). These studies also highlighted that instrumentation and monitoring of landslide sites are essential for understanding and designing short-term and long-term mitigation strategies.

Study area

The study area lies in the Dharan-Dhankuta road, covering 100m long road section, which has been experiencing ground subsidence since the inception of the road in 1987 (Fig. 1). A landslide was triggered due to heavy rainfall in 1987, causing 4 m settlement in the 100 m section of road, which further subsided by 5 m by 1988 earthquake (Hearn, 2002). The area has been affected by continuous movement causing significant subsidence of the highway ever since (Hearn and Martin, 2022). The most recent landslide occurred in August, 2020, subsiding 3 m road that needed temporary road closure and emergency remedial actions. This necessitates a comprehensive investigation for proposing short and long-term remedial measures.

The regional geology of the Guthitar landslide consists of the lesser Himalayan zone (Fig. 2). The landslide is located in Chiuribas, Raguwa and Okhre formations of lesser Himalayan zone containing phyllite, schist, slate, metasandstone and quartzite. The Main Central Thrust (MCT) is located at a considerable distance from the study area, as is another thrust known as the Chimara Thrust.

While no direct evidence of recent fault rupture appears have been detected in the Dharan-Dhankuta area, there was significant ground shaking close to the MBT and MCT in the 1988 and 2011 earthquakes (Hearn and Martin, 2022).

METHODOLOGY

Field Investigations

The field survey identified visible slope movements, such as cracks and settlements with colluvium and fractured rocks. Small-scale landslides are observed with some tension cracks within the DSL. The bedrock, consisting of phyllites and quartzites, was extensively fractured and weathered (Fig. 3). All these geomorphological features, tension cracks,

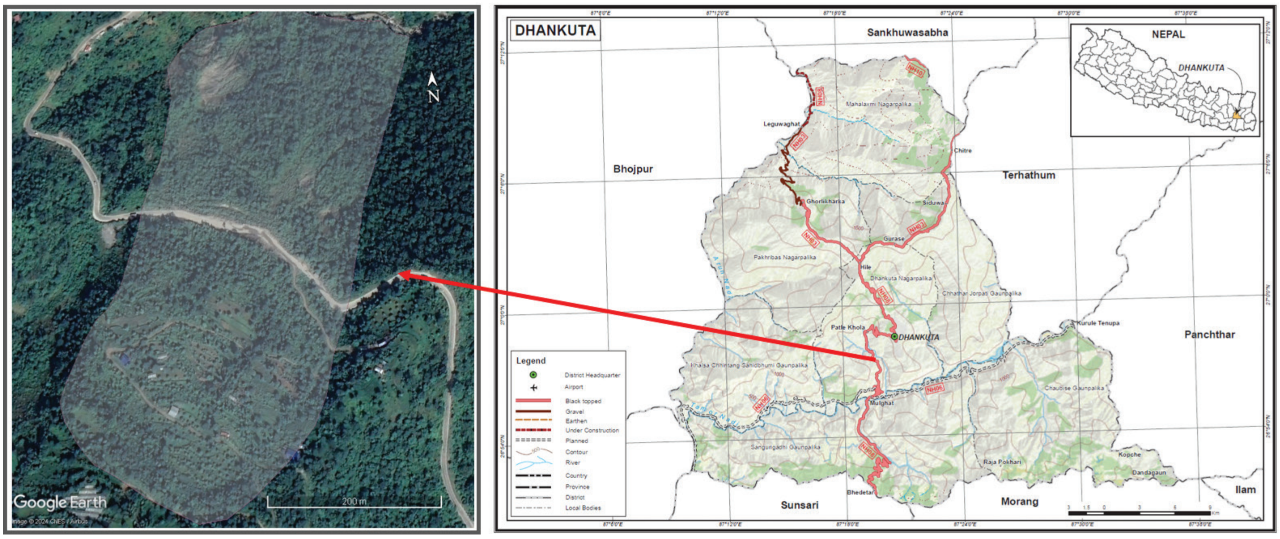

Fig. 1: Location of the Guthitar landslide (Modified after SNH-2020/21).

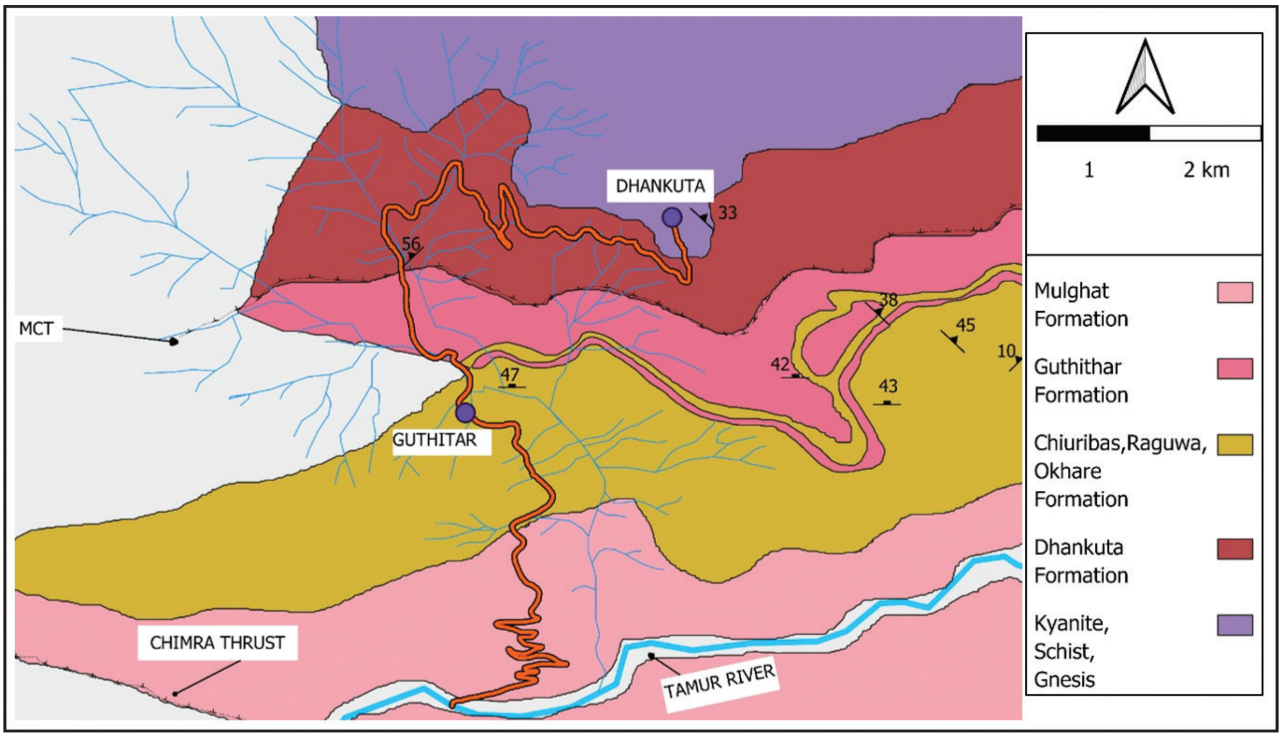

Fig. 2: Regional geological map of the area (After Dhital, 2015).

and geological characteristics were collected during the filed survey to prepare an engineering geological map.

Geophysical

The Electrical Resistivity Tomography (ERT) surveys were conducted in two distinct orientations: one perpendicular to the slope and another parallel to it, in order to encompass and capture the various features of the entire study area (Fig. 4 a). The ERT survey along the slope revealed several distinct layers of lithology, including highly compacted saturated soil, dry colluvium, bedrock, and fractured bedrock. Additionally, multiple perched aquifers were identified beneath the dry colluvium, and some springs were observed at various locations (Fig. 4b). The ERT analysis reveals multiple slip surfaces, with depths ranging from 10 m to 35 m. Furthermore, the ERT indicates the presence of bedrock at a depth of 25 m extending from the riverbank to 300 m upslope. On the upslope side of the highway, fractured rock, and colluvium are observed at the surface. The rock exhibits high resistivity, likely due to extensive fracturing, indicating potential instability (Fig. 4 c).

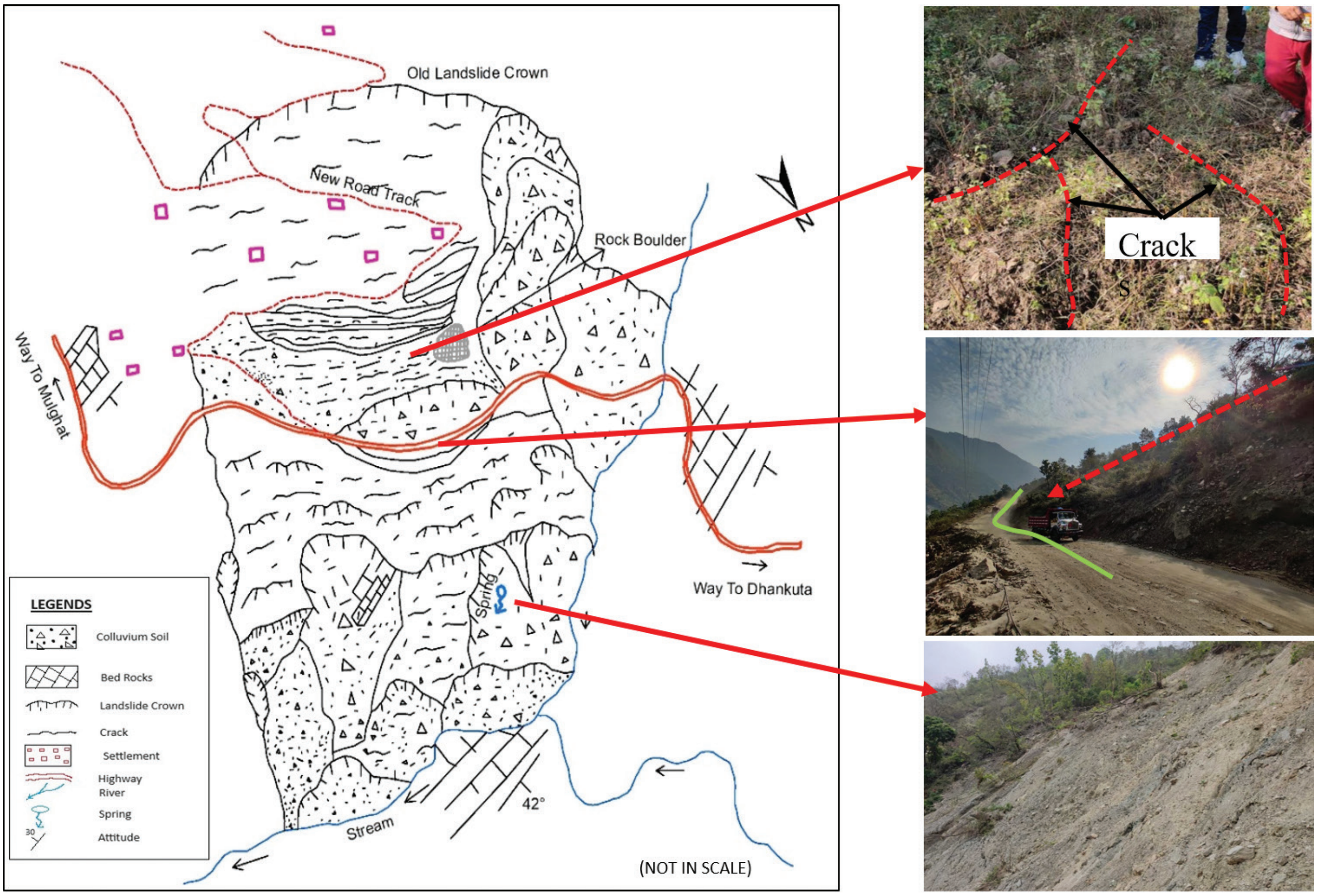

Fig. 3: A sketch showing engineering geological features of the landslide including visible slope movements.

Geotechnical exploration

The geotechnical study was performed by drilling at 3 borehole locations (Fig. 4b). These three boreholes were drilled at varying elevations along the central axis of the unstable slope. Borehole 1 (BH1) and Borehole 3 (BH3), positioned at the top and bottom of the slope, respectively, were both drilled to a depth of 30 m. Borehole 2 (BH2), situated at the midpoint of the slope at road level, reached upto a depth of 15 m. The depths of these boreholes were determined by considering factors such as anticipated failure depth and the presence of bedrock. The BH1 encountered gravelly sand from the ground surface down to approximately 20 m, followed by silty/clayey gravel extending to 30 m with the occasional presence of boulders. Weathered schist boulder was identified up to 20 m, transitioning into granular quartz and bluish-grey meta-sandstone boulders at depths of 24-27 m. BH2 revealed brownish-yellow silty sand up to 6 m, transitioning into coarse to medium-grained sand with gravel down to 15 m. BH3 encountered brownish-yellow gravelly sand up to 9 m, followed by gravelly sand with some fines from 9-21 m, and sandy gravel from 21-30 m with occasional boulders. The water table was not documented during the exploration in any of the boreholes.

The laboratory investigations (Table 1) were conducted alongside standard penetration test (SPT) values obtained in the field. These data were then utilized to model the slope for numerical analysis. The SPT values indicate the presence of boulders, fragmented rocks, or bedrock within the soil strata. However, the collected sludge was deemed representative of the soil's shear behavior, with field SPT values guiding the determination of elastic parameters for soil slopes.

Table 1: Soil properties from sieve analysis and direct shear test

BH	Depth (m)	ϕ(°)	c (kPa)	USCS
	0-1.5	32.62	-	SP
	1.5-3	37.62	-	SP
1	12.5-14.5	35.86	-	SP
	16-17	34.24	-	SP
	20.5-21	35.43	-	SP
	1.5-3	27.45	3.24	SP
2	5-6.0	32.87	1.51	SW
	9-10.5	34.26	-	SP
	12-13.5	38.01	-	SP
	0-1.5	34.01	-	SP
3	6-8.0	38.14	-	SW
	13-14	36.02	-	SW

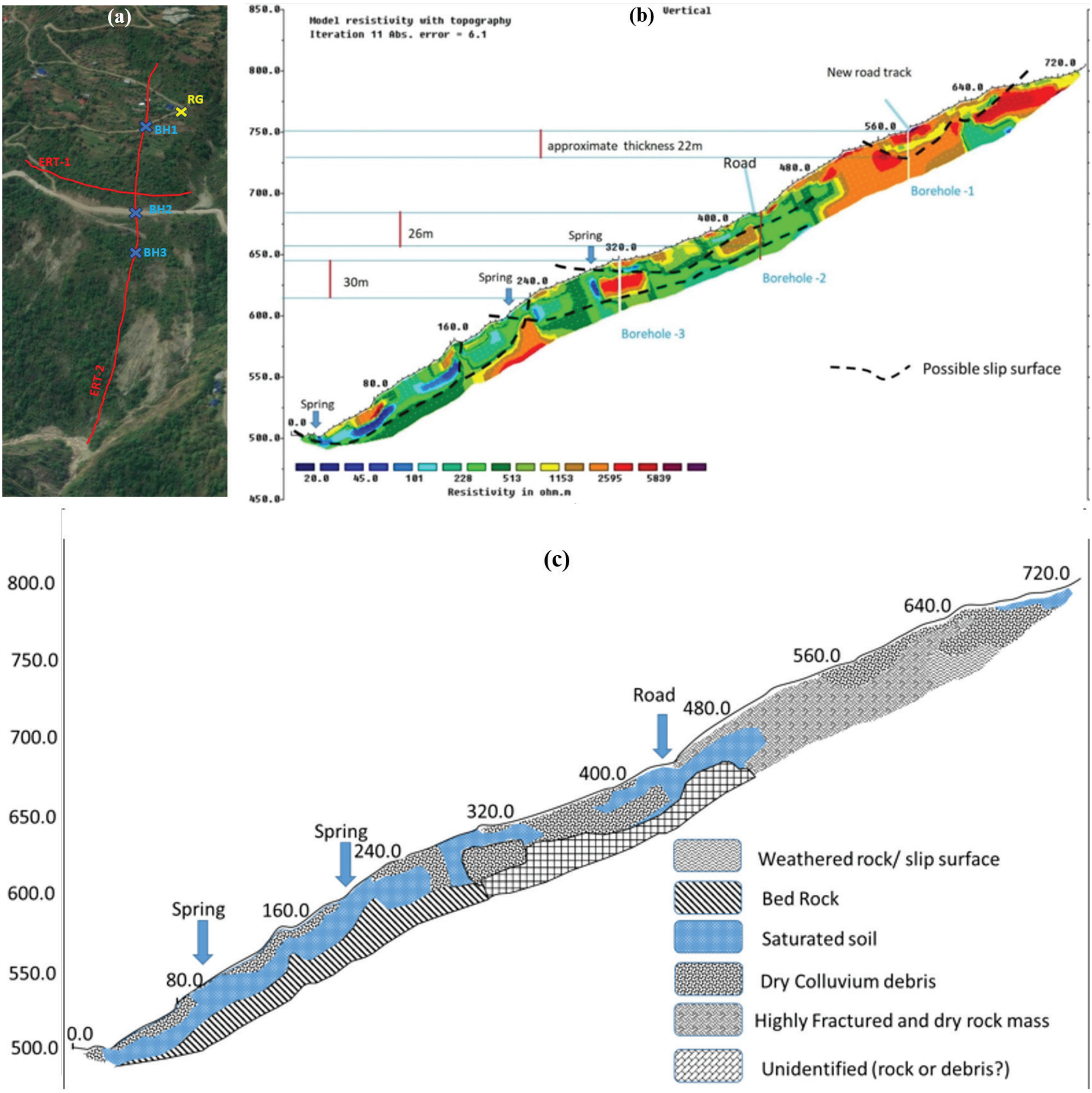

Fig. 4: Geophysical survey (a) Layout, (b) Resistivity profile, and (c) Interpreted subsurface strata.

Numerical analysis

To ascertain the stability of a slope, it is imperative that the forces resisting slope failure outweigh those causing it (Duncan et al., 2014). The 2D numerical model of the landslide utilizing GeoStudio with SLOPE/W was employed for LEM analysis and Plaxis 2D for SRM analysis to scrutinize movement patterns. The initial hillslope geometry served as the baseline, with subsequent adjustments made to surface geometry and stratification (Fig. 5). The Mohr-Coulomb Model was chosen as the constitutive model for soil stability analysis. Material properties were derived from laboratory test data, supplemented by correlations from SPT results (see Table 2). Despite the predominantly gravelly sand composition of the soil, a nominal cohesion value was assigned for the numerical convergence (Table 2).

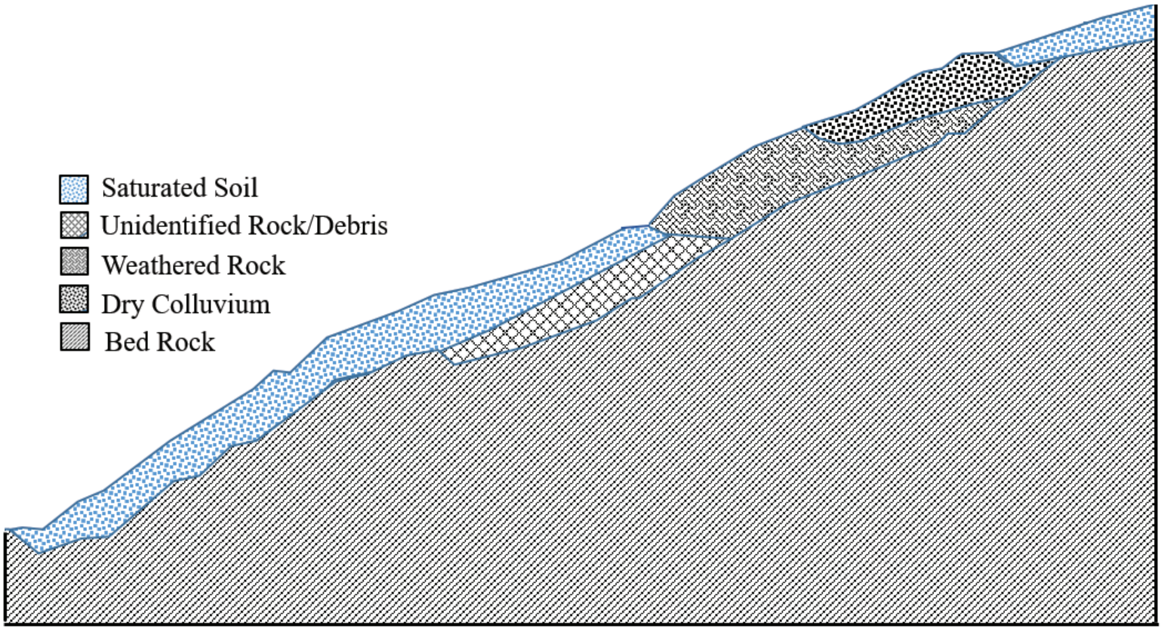

Fig. 5: Geometry and simplified subsurface layer used in analysis.

Table 2: Soil parameters used in the analyses

Soil Type	Material Model	Drainage Type	Unit Weight (kN/m³)		Shear Strength Parameters		Stiffness Parameters	
			γ	γ_{sat}	c (kPa)	$\phi(°)$	E (kN/m²)	ν
Dry colluvium debris	MC	Drained	17.5	18.5	2	35	14500	0.3
Highly fractured and dry rock mass	MC	Drained	17.5	18.5	2	33	19000	0.3
Saturated soil	MC	Drained	17.5	18.5	2	30	15000	0.3
Unidentified rock layer	MC	Drained	17.5	18.5	10	40	20000	0.3
Bedrock	MC	Non-porous	24	24	2000	40	1E+07	0.2

RESULTS AND DISCUSSION

Numerical analysis

The LEM analysis indicated that the upper part of the slope remained stable, with a Factor of Safety (FoS) of 1.364. However, localized slope failure occurred at the road level, where the Factor of Safety dropped to 0.918 on the weakest slope. This analysis shows a continuous subsidence of the road level in the field. Beneath the road section, multiple slip surfaces were identified with FoS of 0.942 and 0.962 (Fig. 6 a). Additionally, according to the SRM, the initial FoS of the slope was 0.75, particularly for the small shallow seated failure of the slope just above the road section as documented during the investigation. The anticipated FoS for the slope should ideally range between 0.9 to 1, a value that would become evident once the weakest slope is stabilized. Various failure planes were detected still after the stabilization through changes in phase strain (Fig. 6 b). In particular, the critical failure plane was detected at a depth of 10 meters just below the road section, while the surfaces extend down to 17 m at the location where inclinometer monitoring took place.

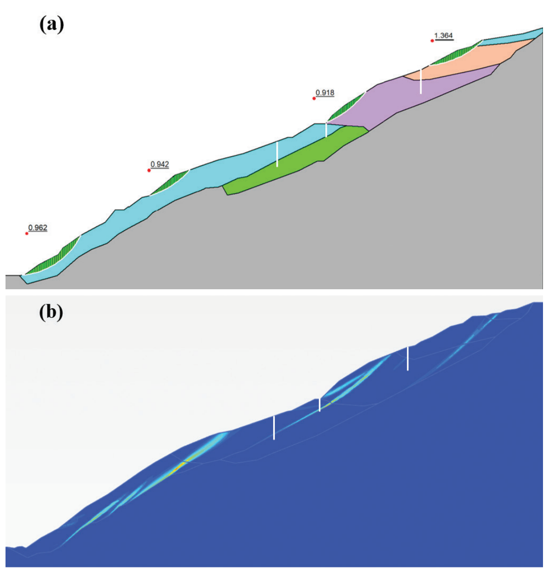

Fig. 6: Failure surfaces obtained from different methods a) LEM, b) SRM.

Slope monitoring

The ground deformation was monitored using the inclinometer. The presented data represents the deformation observed at a specific point on an unstable slope, reflecting the cumulative movements occurring across the entire depth of the slope. Monitoring of ground deformation was conducted at BH1 and BH3 boreholes, with BH3 data primarily used for comparison with numerical analysis. Over a year of continuous monitoring from November 2022 to October 2023, significant movement towards the downslope direction (A+) and across the slope direction (B+) was recorded, totaling 62.94 mm and 19.77 mm, respectively. Maximum differences in deflections occurred at a depth of 11.5 m along both A and B axes, indicating this depth as the probable slip surface at BH3. Notably, a substantial portion of the A+ direction movement, 44.75 mm, occurred within the initial four months of monitoring, with a further 14.91 mm observed in the final third of the monitoring period. The SRM analysis identified a distinct failure plane beneath the site showing a deformation profile, however, there was a discrepancy between the predicted and observed slip surfaces: slope monitoring indicated a depth of 11.5 m while the SRM analysis suggested 17 m. Both the field monitoring results and the numerical analysis are consistent with borehole logs, which show the presence of fines from a depth of 9-20 m. It's important to note that discrepancies between subsurface displacement monitoring and numerical analysis are common (Pamuk et al., 2021). This suggests that predictions using numerical analysis should be made cautiously with expert judgment because the parameters used in the model are often derived from SPT correlations. Additionally, the shallow slip surface observed in monitoring could be due to other shallow slip surfaces and inconsistencies not detected during soil investigations highlighting the importance of ground monitoring for accurately understanding ground deformation.

Rainfall and slope deformation

Figure 8 presents both rainfall data and cumulative surface deformation. The abnormally high rate of movement was observed within the first 4 wk, which can be attributed to the voids and fractures of ground around the casing. Then, the rate of movement was about 0.3 mm/wk. After about 8 wk of heavy rainfall infiltration on the ground, the rate of movement increases to around 1.2 mm/wk. A substantial increase in slope movement after an extended period of rainfall was observed, especially after 37th wk. This marked escalation strongly suggests a correlation between prolonged precipitation and increased slope movement. It implies that after extended rainfall, soil moisture rises, and the increase in moisture content within the slope likely causes a loss of shear strength, increasing instability and leading to increased movement rates (Pradhan et al., 2022; Wang et al., 2023). Based on these findings, implementing effective drainage management strategies is considered as potential solution to mitigate the increased slope movement.

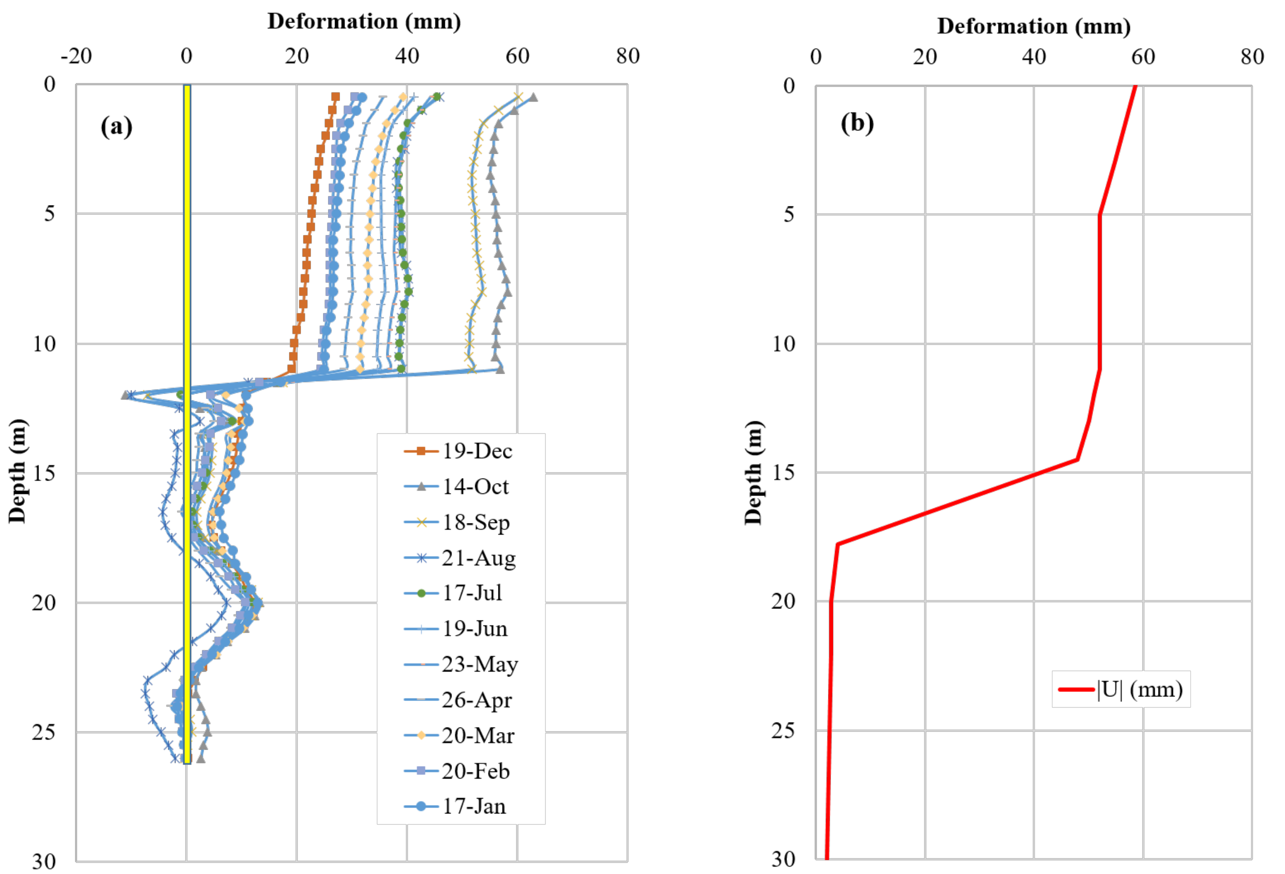

Fig. 7: Deformation pattern obtained from a) Slope monitoring, b) FEM analysis, at BH3.

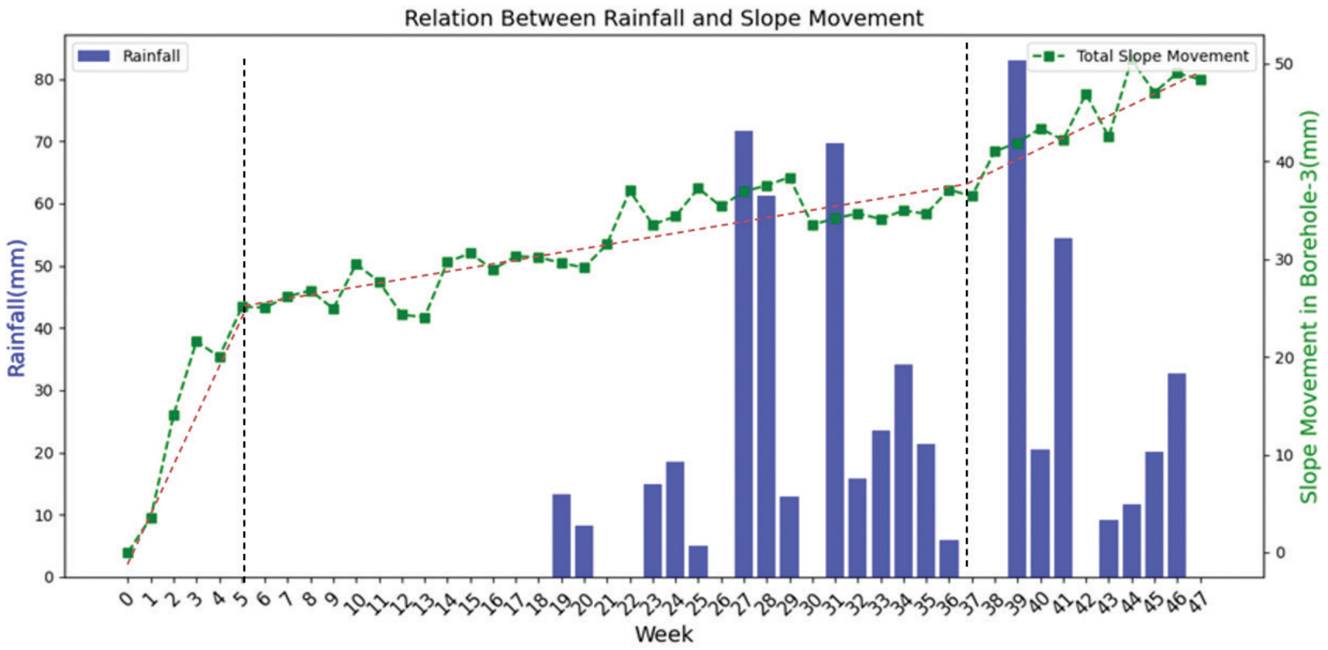

Fig. 8: Correlation between rainfall and slope movement.

Understanding landslide dynamics and its implications

The causes of landslides can generally be grouped into tectonic, geological, geomorphological, and anthropogenic factors (McColl, 2015), with rainfall and earthquakes serving as primary triggers (Dahal and Dahal, 2017; Dahal, 2012; Pyakurel et al., 2023). The Gorkha earthquake's intense ground shaking was not only felt in central Nepal but also significantly impacted the eastern region (Martin et al., 2015). In addition, the heavy rainfall in 2020 was a major trigger for increased ground movement (Hearn and Martin, 2022). The primary factor contributing to the movement is the soil layer found at depths of 9-20 m, which contains some fine materials. Additionally, small-scale landslides occurring in the lower section, particularly along the stream (as shown in Fig. 2), have contributed as toe removal, thereby exacerbating the movement.

Landslide investigation, monitoring and analysis are important on understanding the dynamics of the landslide (Wasowski and Pisano, 2020), and landslide management and mitigation highlighting its importance for both short-term and long-term strategies. Immediate measures for mitigating shallow-seated landslides and tension cracks might include the use of reinforcing elements and improved drainage management. However, addressing DSL requires more expensive and complex mitigation techniques. Long-term monitoring is essential to understand the temporal variability of different triggering factors and their effects on slope movement and to develop a comprehensive management strategy (Hu et al., 2024). Satellite imagery can further enhance the analysis of long-term deformation in the study area. While some landslides, such as the Slumgullion landslide, have been monitored using various techniques including field surveys, GPS, and InSAR (Wang et al., 2018). These methods also have limitations, for instance; InSAR may not be effective for monitoring fast-moving landslides. Field instrumentation, though costly, remains the most accurate method for capturing deformation patterns across different slope depths, while remote sensing techniques cannot achieve this (Chen et al., 2021). The observed patterns between ground deformation profiles obtained from monitoring and numerical analysis in this study validate the complementary nature of these approaches.

Finally, this study enhances the understanding of DSL dynamics in the Himalaya and evaluates the strengths and limitations of various methods for analyzing such landslides. After adjusting for initial data and extrapolation, the movement rate was determined to be 35 mm/yr. This rate is sufficient to cause failure in rigid structures within the landslide body, including drains and retaining walls, which could worsen the situation and accelerate movement.

CONCLUSIONS

The investigation and analysis of the Guthitar landslide along the Dharan-Dhankuta road provide critical insights into the complex dynamics of deep-seated landslide movement in the Himalayan region. The combination of field instrumentation, including inclinometers and rain gauges, with numerical slope stability analysis revealed the limitations of relying solely on computational methods. The discrepancy between the slip surface depth identified through field monitoring (11.5 m) and that predicted by numerical analysis (17 m) underscores the importance of integrating on-site measurements with analytical models for accurate landslide assessment. Furthermore, the observed annual deformation of 35 mm, along with the increased rate by three folds after prolonged rainfall, underscores the urgent need for both short-term and long-term mitigation measures to protect critical infrastructure.

Overall, this study highlighted the importance of landslide field monitoring systems for the effective mitigation and management of landslides in regions characterized by fragile lithology along with rugged topography. These findings underscore the necessity for continued and enhanced field monitoring to inform and implement appropriate landslide management strategies in the Himalayas, which frequently experience heavy monsoon rains and earthquakes.

AUTHOR'S CONTRIBUTIONS

B. K. Dahal conceptualized the work. B. K. Dahal, B. R. Adhikari, and S. Lamichhane planned the field investigation, verified and interpreted the field data, reviewed the results, and wrote the manuscript. P. R. Gautam synthesized the field data and conducted the laboratory tests and numerical analysis. D. Gautam prepared the sketch with engineering geological features. All authors discussed, reviewed, and finalized the paper.

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