Geoenvironmental Disasters

RESEARCH

Open Access

Sustainable rural infrastructure: guidelines for roadside slope excavation

Prabhat Paudyal[1], Pranish Dahal[2], Prakash Bhandari[3] and Bhim Kumar Dahal[1*]

Abstract

The construction of non-engineered, equipment-based rural roads in Nepal Himalaya is one of the predominant causes of landslides. The construction frequency of such roads has significantly increased over the past decade. However, the present guidelines governing slope excavation for these roads are not based on geotechnical characterizations of sites. The current study uses the limit equilibrium method with the Mohr–Coulomb constitutive model to determine safe cut heights and slopes for varying geometric and material parameters. GeoStudio Slope/W was used to model soil slopes with various gradients, and cuts with varying depths and slope angles were modeled to calculate the factor of safety (FoS) against shear failure for different geometric and material conditions. The results of the study were visualized in design charts with FoS as the dependent variable. The analysis highlights the importance of different parameters, i.e., excavation depth, excavation slope, and existing ground slope in the FoS, in addition to the slope-forming material. Furthermore, a field study was carried out to validate the model using the clustering approach. The results from the field are similar to those from the numerical model, although some additional site-specific parameters like vegetation cover and surface runoff conditions should be considered before selecting the cut slope. Finally, this study proposes that future road construction guidelines should consider terrain parameters, hydrology, and geotechnical site conditions to promote sustainable road infrastructure and reduce future disaster risks in the Himalayan region.

Keywords Excavation guidelines, Slope stability, Limit equilibrium, Mohr–Coulomb failure criterion, Rural roads

Introduction

Currently, one of the most dynamic developments happening in rural areas is the construction of roads. However, the critical factor of slope stability has not been adequately addressed during road construction. As a result, a large number of landslides have been observed near the newly constructed rural roads (Scott Wilson 2003). Figure 1, sourced from Google Earth shows a typical example of a change in the landscape due to road construction-induced landslides. There is a significant amount of literature available that describes the relationship between landslides and road construction and maintenance practices in Nepal (Hearn and Shakya 2017; Ives et al. 2003). Along with earthquakes and rainfall, poor road construction practice is one of the major reasons for landslides in Nepal (McAdoo et al. 2018). Petley et al. (2007) attributed poorly constructed roads as one of the major reasons behind the dramatic increase in landslide fatalities in Nepal between 1978 and 2005. Froude and Petley (2018) found that in Nepal 43% of all road construction-triggered landslides occurred during road construction. These landslides not only cause loss of property and life but also result in the degradation of rural road networks, which in turn necessitates a significant increase in maintenance costs (Scott Wilson 2003). The main reasons behind increased slope instability in rural roads are decentralization and change in administrative

*Correspondence:
Bhim Kumar Dahal
bhimd@pcampus.edu.np
[1] Institute of Engineering, Tribhuvan University, Pulchowk Campus, Lalitpur 44700, Nepal
[2] Utah Water Research Laboratory, Utah State University, Utah 84321, USA
[3] University of Connecticut, Connecticut 06269, USA

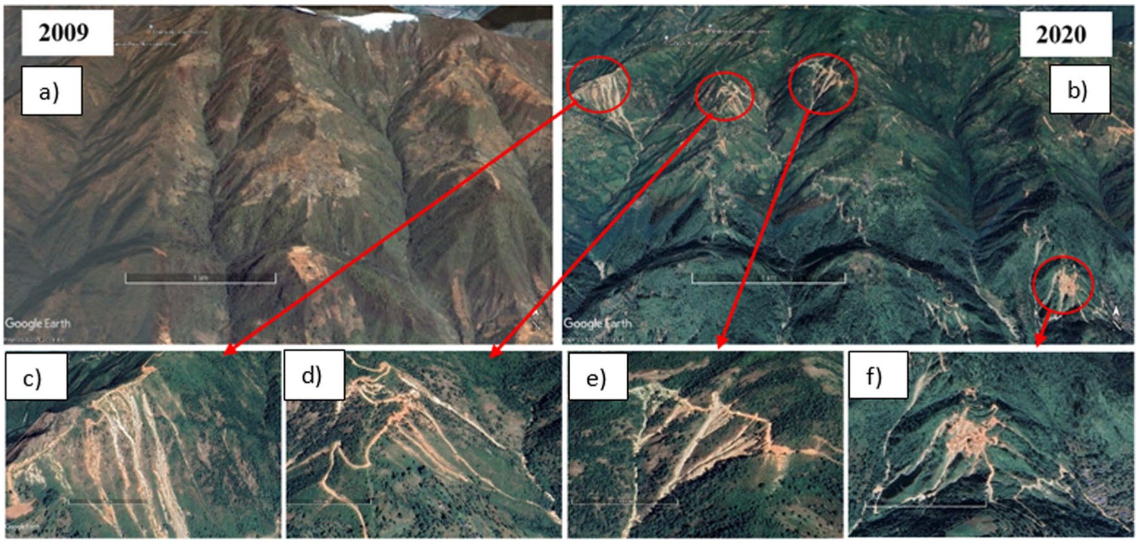

Fig. 1 A rural hillslope in Kurintar, Nepal in 2009 (**a**) and 2020 (**b**). Four large landslides (**c**–**f** outlined in red) occurred here as a direct consequence of the construction of a rural road

control of rural roads, shift from labor-based to equipment-based construction, and lack of proper guidelines.

Roads in Nepal are generally classified as national highways and Feeder roads (i.e., strategic road network, SRN), and local roads (i.e., local road network, LRN). The former falls under the jurisdiction of the Department of Roads (DoR), while the latter falls under the jurisdiction of the Department of Local Infrastructure (DoLI; formerly DoLIDAR: Department of Local Infrastructure and Agricultural Roads). Most rural roads fall under LRN, the development of which has been a priority for the government of Nepal for the past two decades, and it is expected to continue as the country shifts to a decentralized federal government structure. As a consequence, there are now concerns about the ability of newly-formed local and provincial governments to establish safeguards to ensure that the benefits of the rapid development of road networks outweigh the potential losses (Rankin et al. 2017; Sudmeier-Rieux et al. 2019). The local level governments have started to build many vehicular roads in the rural areas just by expanding foot trails already being used by the community residing in those areas, without engineering oversight (McAdoo et al. 2018). Due to limited budget and time constraints in such construction, the implementation of roadside structures and landslide mitigation measures such as retaining walls, bio-engineering measures, etc. are often overlooked.

In the past, the construction of low-cost rural roads was implemented using more sustainable and labor-based methods. A design and construction approach labeled as the green road approach (Acharya et al. 1999) was proposed in 1999. The practice of mass balance—whereby the excavated material is used as the fill material to reduce the cut height as far as practicable, was introduced in the approach (Fig. 2). Phased construction, such as the gradual increase of the width of the road eliminates the need to manage large amounts of excavated material and allows for the natural compaction of earthwork by monsoon rains (Acharya et al. 1999; Klatzel 2000; Mulmi 2009). However, the problem with all these approaches is that they are slow, and require extensive retaining structures if the cross-slope is greater than 35% (Lawrence and Hearn 2002). In addition, the green road approach, which emphasizes labor-based construction, necessitates a large upfront financial investment. As per the rate analysis norms of the Department of Roads (DoR), manual road cutting of one cubic meter requires a labor input of 0.75 person-days, whereas the same quantity of cutting carried out using mechanical means requires only 0.011 person-days of labor input, a reduction of labor by 98.5%. Additionally, the duration for excavating one cubic meter using labor-based methods is 6 h, whereas, for mechanical excavation, it is 0.017 h (DoR 2018).

Rural road construction in Nepal has moved from being a primarily labor-based (LB) approach to an equipment-based (EB) practice in the last 20 years. The use of heavy equipment to construct unplanned roads and the disregard for slope protection works are often observed in the EB road construction practices in Nepal (Hearn and Shakya 2017; UNEP and UNDP 2011). This is evident in the emergence of EB construction practices, the roads constructed by local heavy equipment operators in collaboration with politicians lack basic grading, appropriate excavation slope, slope mitigation, and drainage

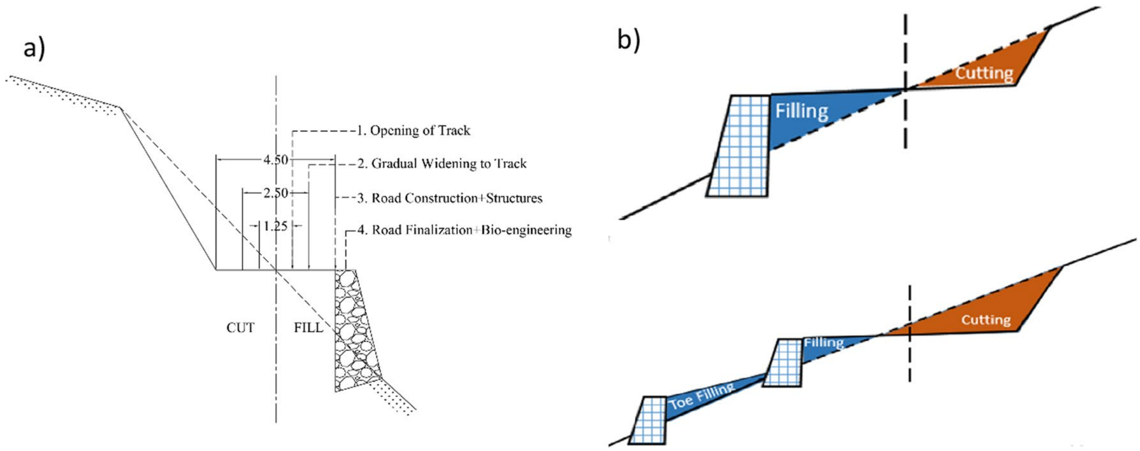

Fig. 2 **a** Green Road approach (after Acharya et al. 1999); **b** mass balance approach (after NRA 2021)

Table 1 Cut slopes for road excavation in Nepal Road Standard (DoR 2014)

Soil type	Cut slope (V:H)
Ordinary soil	1:2 to 1:1
Disintegrated rock or conglomerate	1:1/2 to 1:1/4
Soft rock, shale	1:1/4 to 1:1/8
Medium rock	1:1/12 to 1:1/16
Hard rock	Almost vertical

structures. Moreover, this practice often results in road failures and subsequent costly repairs during the immediate monsoons, which fall between June and September (ITAD 2017; Singh 2018; Sudmeier-Rieux et al. 2019).

Apart from governance and political factors, Robson et al. (2022) attributed the lack of user-friendly and scientific guidelines covering roadside excavation as one of the reasons behind road construction-induced landslides. The design and construction of the SRN are governed by the Nepal Road Standard, NRS (DoR 2014). The design and construction of the LRN are governed by the Nepal Rural Road Standards, NRRS (DoLIDAR- Department of Local Infrastructure Development and Agricultural Roads 2014). The latter does not contain any slope excavation guidelines, further exacerbating the trend of the construction of non-engineered roads. NRS contains a guideline to determine the maximum slope of excavation according to observed rock and soil characteristics on site (DoR 2014), but the biggest caveat of this guideline is the classification of materials. Different materials have been classified into 5 classes while all types of soils are lumped into a single group (Table 1).

Further, DoR has recommended the excavation depths and slopes for road construction in its 2003 guidelines for slope protection works (DoR 2003). These guidelines (Table 2), although more comprehensive than those of the NRS, are difficult to implement for the LRN because they are intended for well-engineered (generally SRN) roads, which are constructed under the supervision of well-trained engineers of the DoR with proper implementation of drainage and slope stability measures. While field observations have revealed that soil cut heights are drastically smaller in the LRN than in the SRN. Therefore, there is an urgent need for user-friendly guidelines based on geotechnical characterizations for rural road engineers (Robson et al. 2022).

The stability guidelines or charts presented above and others like Overseas Road Note 16, 1997 (Lawrence and Hearn 1997) are useful in the case of proper geotechnical characterization, which generally requires proper site investigations with in-situ and laboratory tests. These guidelines eliminate the need for detailed numerical analysis of each slope in well-engineered roads. However, low to mid-level technicians (Overseers and Sub-Overseers in Nepal) could struggle to use published stability charts/guidelines, an alternative to detailed numerical analyses, due to a lack of understanding of geotechnical engineering (Robson et al. 2022). Therefore, the development of road excavation guidelines based on simplified field characterizations of geotechnical parameters and other easily identifiable data like ground cross-slope is invariably important for low-cost road construction. However, none of the published roadside excavation guidelines in Nepal delineate the safe slope of excavation in terms of the Factor of Safety (FoS) incorporating those parameters.

Table 2 Road cut slope excavation guidelines (DoR 2003)

	Soil classification	Cut slope (H:V)		
		For < 5 m cut height	For 5–10 m cut height	For 10–15 m cut height
Sand	Loose, poorly graded	1:1.5		
Sandy soil	Dense or well graded	1:0.8–1:1	1:1–1:1.2	–
	Loose	1:1–1:1.2	1:1.2–1:1.5	–
Sandy soil, mixed with gravel or rock	Dense or well graded	1:0.8–1.1		1:1–1:1.2
	Loose, poorly graded	1:1–1:1.2		1:1–1:1.2
Cohesive soil		1:0.8–1:1.2		-
Cohesive soil mixed with rock or cobbles		1:1–1:1.2	1:1.2–1:1.5	-

Materials and methods

The present study evaluates the FoS for different cut slopes and heights in various soil types and ground slopes using the Morgenstern–Price (M–P) method in GeoStudio Slope/W 18 (GeoSlope 2018), validated by field survey and presented in user-friendly charts for safe excavation depth. The implementation involves the classification of soil based on the Nepal Reconstruction Authority's soil identification procedure (NRA 2021), and the study suggests correction factors for water table variation and soil saturation due to rainfall effects. This section outlines the detailed methodology, including numerical modeling and field validation.

Numerical modeling

The Morgenstern–Price (M–P) method (Morgenstern and Price 1965), a Limit Equilibrium (LE) method was used in the study using the Mohr–Coulomb (M–C) failure criterion (Chen et al. 1969; Taylor 1937). The numerical analysis using staged construction was performed in GeoStudio Slope/W 18 (GeoSlope 2018) software by removing materials to mimic cutting. The design charts indicated the maximum cut height and cut slope required such that the FoS of slopes remained within generally accepted limits. A procedure for correcting the FoS results after adjusting them for rainfall events was then developed.

Slope geometry

In this study, ground slopes (GS) less than 20% (Vertical:Horizontal, V:H) were excluded as the primary focus was on hill slopes. However, the numerical analysis was also conducted for 10% slopes, and the results were found to be consistent with those of 20% slopes. Therefore,

Table 3 Slope geometry information

Cross-gradient (V:H in percentage)	Cut height (m)	Cut slope (V:H)
20	1	0.5:1
30	2	0.667:1
40	3	1:1
50	4	2:1
60	6	3:1
	8	4:1

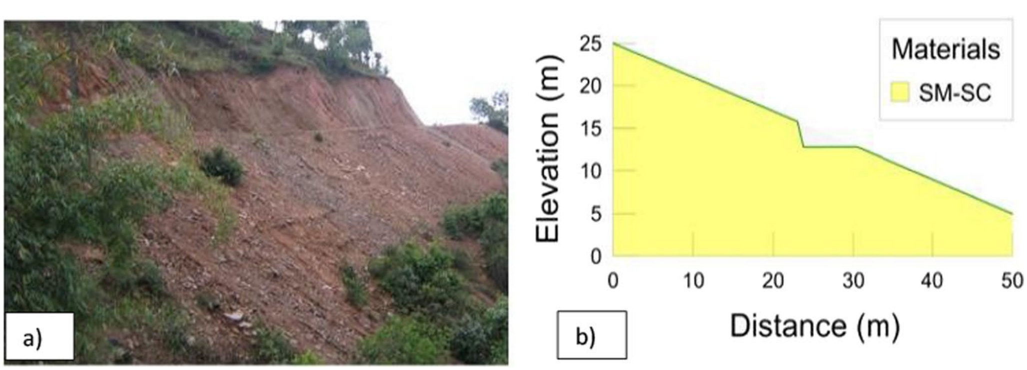

Fig. 3 **a** A typical rural road cross-section pictured in Nepal; **b** idealization of the road cross-section in GeoStudio Slope/W

slopes ranging from 20 to 60% GS were considered for the analysis. In addition, slopes with GS values greater than 60% were not considered as such steep slopes are typically composed of rock and are outside the scope of this study. Six different cut heights ranging from 1 to 8 m were considered for slopes with cut slopes ranging from 0.5:1 to 4:1 (V:H). The GS values were selected based on the terrain classification in the NRS, while the cut heights were chosen to best represent typical rural roads being constructed in Nepal, based on several field observations (Table 3, Fig. 3a).

Material modeling

The materials of all slopes considered in the study are assumed to be homogeneous and isotropic. Twelve different soil types as per USCS were modeled in the study. The strength parameters were characterized as per the M–C failure criterion, which was selected based on its ability to best represent the failure of weathered rock and alluvial soil, as reported by Hoek and Brown (2019). The M–C failure criterion was also deemed suitable for predicting soil behavior based on field observations due to its requirement for a few input variables.

Based on soil behavior in LE slope stability analysis, various soil types are categorized into six different soil groups: coarse-grained soil (USCS symbol GW, SW, GP, SP), coarse-grained soil with non-plastic fines (USCS symbol SC, SM-SC, SM, GM), coarse-grained soil with plastic fines (USCS symbol SC, GC), silt (USCS symbol ML, MH), low plasticity clay (USCS symbol CL), and high plasticity clay (USCS symbol CH) (Table 4). The M–C parameters of cohesion (c) and friction angle (Φ) were assigned to the soils in this study, along with the unit weight (γ) based on the published literature (Bureau of Indian Standards 1997; Minnesota Department of Transportation 2007; NAVFAC 1986).

Slope stability analysis

The M–P method (Morgenstern and Price 1965) was the LE method used for slope stability analysis using GeoStudio Slope/W 2018. Seepage and pore-water condition was not considered to reduce site-specific variables involved in the numerical modeling. The directional movement of soil mass was considered. The trial slip surface was formulated by manually entering probable entry and exit regions. Tension cracks were not considered and the FoS calculated is the deterministic FoS. The minimum depth of the slip surface was set at 0.1 m. Each slip surface was discretized into 30 slices, with a maximum of 100 iterative calculations per slice. The search algorithm adopted was the non-linear root finder method. Slip surface entry and exit regions were set at the crest and toe of the excavation.

Field study

The purpose of the field assessment was to evaluate the stability of a rural road site in Dadeldhura, Sudurpaschim Province, Nepal, and compare it with the results of the numerical analysis. The study area included 22 different sections of the Anarkholi-Bajkot-Khateda rural road in the Ajayameru rural municipality (Fig. 4). The road is being constructed without technical supervision or alignment design; hence, it can be classified as a non-engineered road. The assessment was conducted between October 11th and 14th, 2022, at the end of the monsoon season. The road passes through various types of land, including cultivated land, settlements, barren land, and dense forest. The road alignment passes through elevation ranges from 1800 to 2300 m, with soil varying from high-plasticity clay to coarse gravel. The region experiences heavy snowfall once a year and heavy rainfall during the monsoon season. Therefore, the road section is taken as a typical case for field validation.

The methodology used for the field data collection involved soil classification and measurements of cut height, cross slope and cut slope. Soil classification was performed by spreading soil samples on the ground and examining them with the naked eye (Fig. 5a). Coarse-grained particles visible to the naked eye were categorized as gravel if their size exceeded 5 cm, while smaller

Table 4 Material modeling information

Soil type	USCS grouping	Cohesion (kPa)	Friction angle (°)	Unit weight, γ (kN/m^3)
Coarse-grained soil	GW, SW, GP, SP	0	37	20
Coarse-grained soil with non-plastic fines	SC, SM-SC, SM, GM	5	34	19.5
Coarse-grained soil with plastic fines	SC, GC	7.5	31	19.5
Silt	ML, MH	16.5	25	17.5
Low plasticity clay	CL	19.5	23	17.5
High plasticity clay	CH	21	18	16

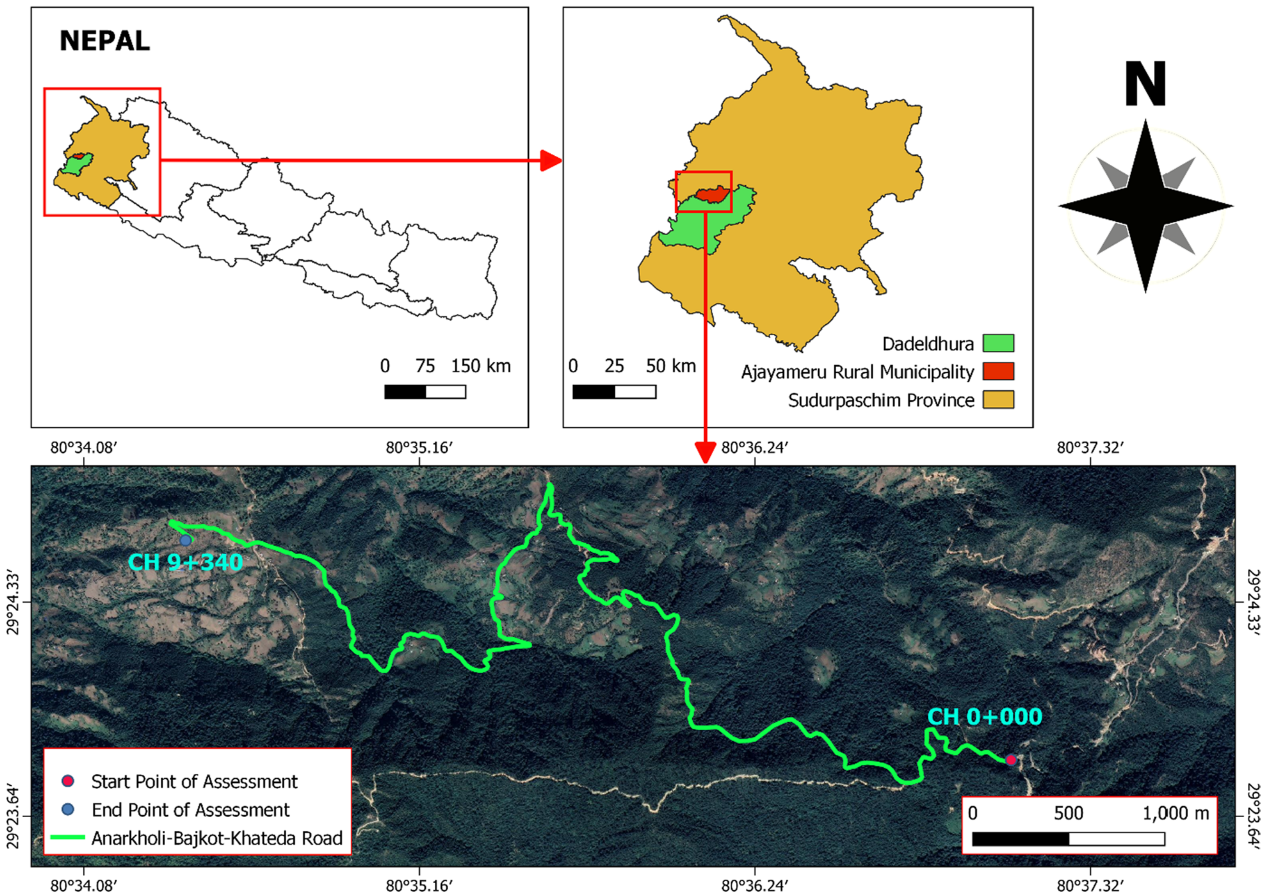

Fig. 4 Location map of Anarkholi-Bajkot-Khateda rural road, Ajayameru Rural Municipality, Dadeldhura, Nepal

particles were classified as sand. The plasticity of the soil was tested by pressing a small lump of soil between the thumbs for fine-grained soil (Fig. 5b) or making a soil ball in the palm for coarse-grained soil. The field observations led to the classification of soil into six categories: gravel, gravel with non-plastic fines, gravel/sand with plastic fines, silt, low plasticity clay, and high plasticity clay. Cut height was measured using a graduated rod of length 5 m, while the ground slope and cut slope were determined with two such graduated roads (Fig. 5c). A schematic representation of the stepping method used to determine both the cut height and cut slope/ground slope is presented in Fig. 5d.

Results

The results of the numerical analysis are presented in this section in the form of design charts. Each design chart is prepared for a set of USCS soil types grouped by similar textural and plastic properties (Table 4).

Coarse-grained soil

The results on cut height versus FoS charts of coarse-grained soils (Fig. 6a) highlight significant observations: they demonstrate that coarse-grained soil has the lowest FoS for all ground slopes and cut slopes compared to other analyzed soil types. This can be attributed to the poor cohesive properties of coarse-grained soils, which play a crucial role in slope stability (Fredlund et al. 1978; Jennings and Burland 1962). Specifically, for all ground slopes, only a 1H:0.5V cut slope is stable (FoS > 1.5) across all cut heights. The results also reveal that FoS decreases with a corresponding increase in cut height across all five ground slopes. This trend can be explained by the destabilization of soil slopes by the change in geometry of the existing slopes (Sutejo and Gofar 2015). Furthermore, for a constant cut height, the FoS variation for changes in ground slope is gradual, indicating similar failure patterns on all ground slopes. Finally, the trend lines of the cut slopes of 1H:2V, 1H:3V, and 1H:4V are closely spaced

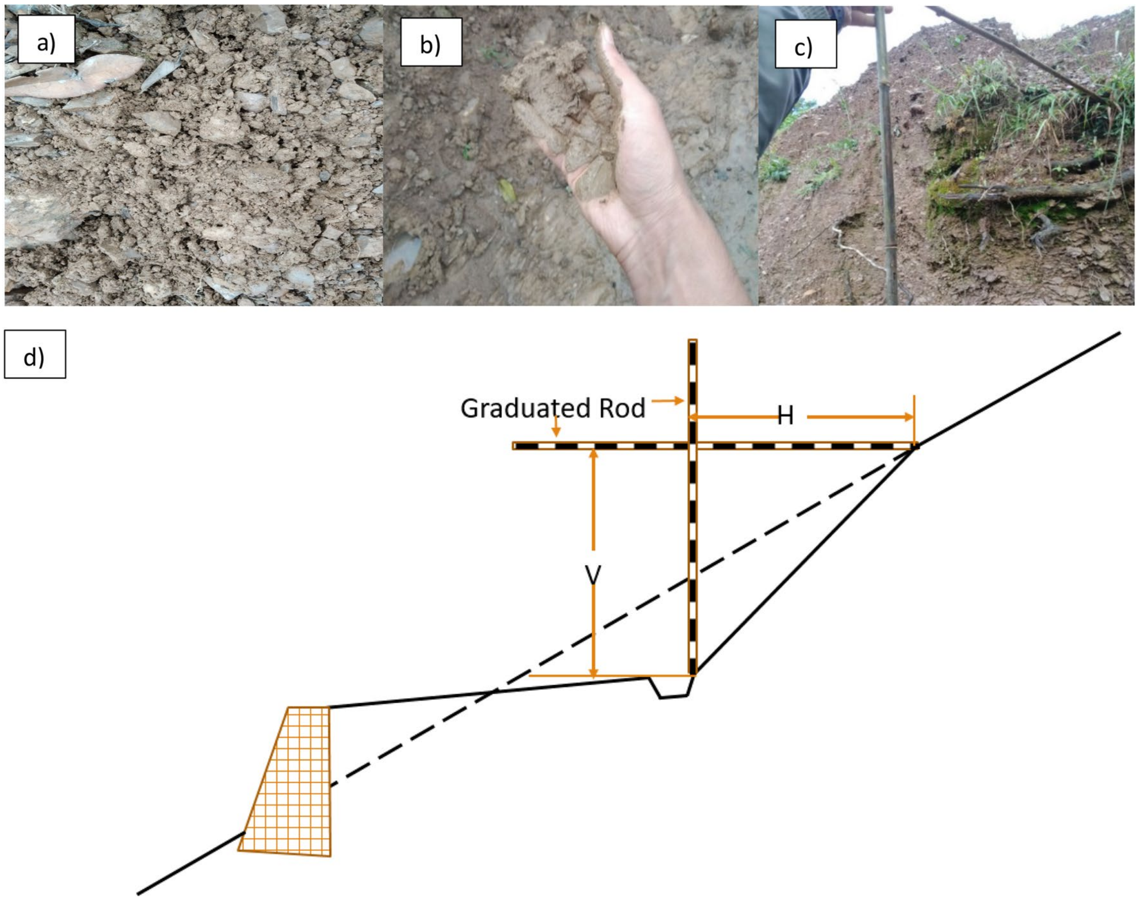

Fig. 5 General field assessment methodology

for all ground slopes, indicating that increasing the cut slope steepness above 1H:2V has little effect on the FoS. These results underscore the critical role of soil properties, particularly cohesion, in slope stability and highlight the need to carefully consider these factors when evaluating the stability of cut slopes.

Coarse-grained soil with non-plastic fines

The analysis of coarse-grained soils with non-plastic fines (Fig. 6b) reveals that the cut height v/s FoS charts exhibit a similar trend to those of coarse-grained soils. Both soil types display a decrease in FoS with increasing cut depth and a gradual variation of FoS for changes in ground slope. Furthermore, the trend lines of the cut slopes for different ground slopes are closely spaced for both soil types. However, a substantial difference arises in the increased stability of coarse-grained soils with the addition of non-plastic fines. Specifically, for all ground slopes, cut slopes of 1:0.5, 1:0.67, and 1:1 exhibit FoS greater than 1.5. This increase in stability can be attributed to the increased cohesion resulting from the presence of fines. The difference in trend lines for the last three cut slopes is minimal in comparison to coarse-grained soils.

Coarse-grained soil with plastic fines

The trend lines of sand with plastic fines (Fig. 6c) are identical in shape to that of sand with non-plastic fines. The main difference is that for each coordinate of FoS v/s depth graphs of all ground slopes, the FoS is higher, barring some exceptions. This is due to the cohesion and friction angle of both soil types being closer to each other. An interesting point to note is the abrupt decrease of FoS when cut depth varies from 4 to 6 m in both 30% and 50% ground slope of clayey sand and fine sand with fines. For both soil types, there is minimal change in FoS when the slope of the cut depth is 1 m and the ground is 60%. This shows that for higher ground slopes with low excavation depth, FoS is independent of cut slope variation, and the trend is followed by clayey soils as well as shown in the subsequent analysis below.

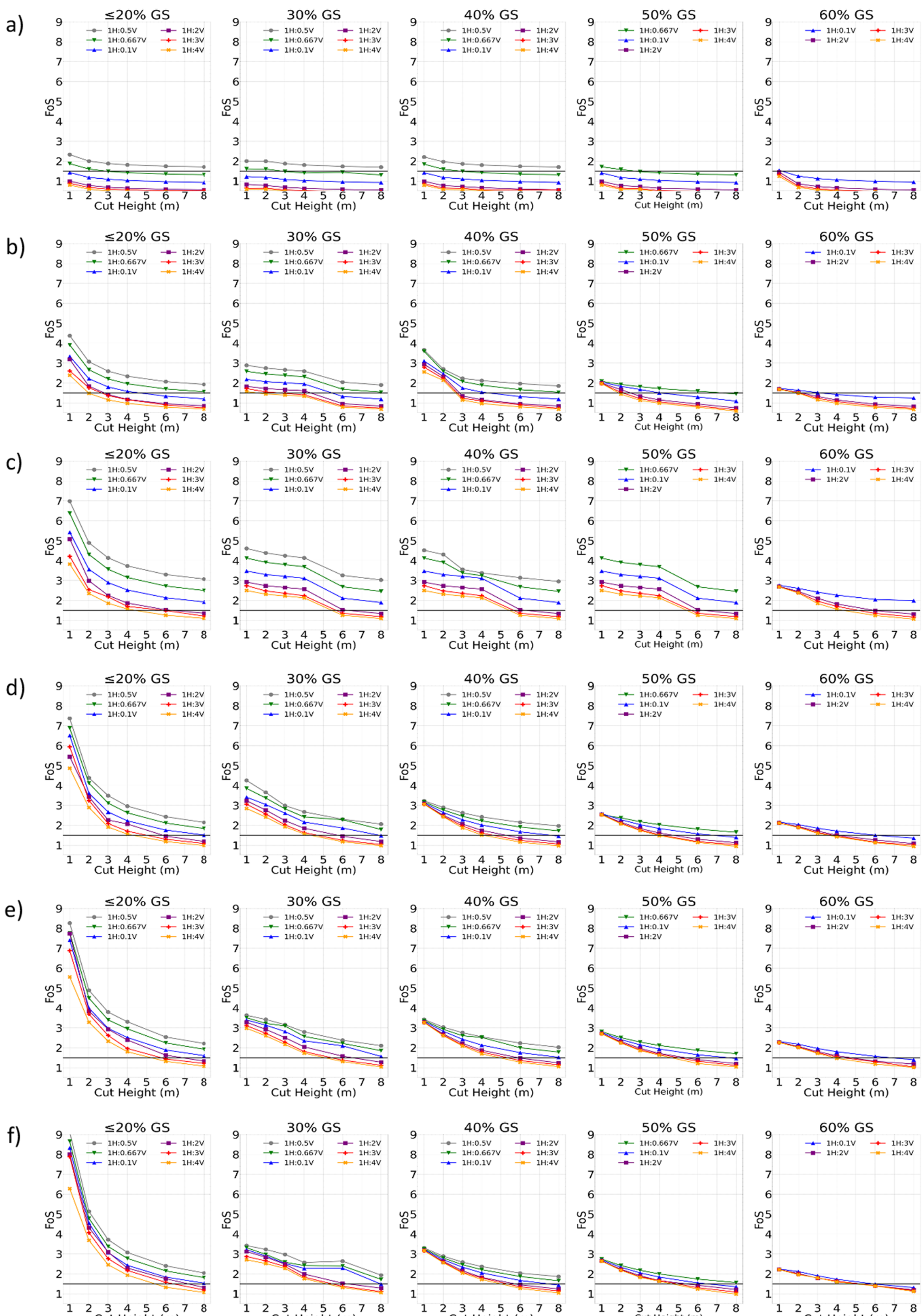

Fig. 6 Cut height v/s FoS charts for: **a** coarse-grained soil, **b** coarse-grained soil with non-plastic fines, **c** coarse-grained soil with plastic fines, **d** silt, **e** low plasticity clay, **f** high plasticity clay

Silt

The trend lines for silts (Fig. 6d) are closely spaced and the FoS deviation is relatively low. It is evident from this result, and the general trend of increase in safety with the corresponding increase in cohesion of the soil, that the increase in cohesion increases the shear strength of soils (Fredlund et al. 1978; Jennings and Burland 1962). Adding to that, as cohesion increases, FoS increases as well for the same ground slope and same cut depth as shown by the graphs above. This can be accounted for cohesion as well. In addition, the abrupt decline in FoS from 4 to 6 m, as in clayey sand and sand with fines, is not followed by silts. Other than these variations, the trend lines for silts are the same in other aspects as that of the above three soil types.

Clay

The trend lines of both low plasticity (Fig. 6e) and high plasticity (Fig. 6f) clay are similar to that of silts. The only noticeable difference is that the FoS of low-plasticity clay is similar to that of silts but high-plasticity clay has the highest point-for-point FoS out of all the six soil types. This is because the cohesion value for clay is the highest among all the soils.

Rainfall parameter adjustment

Rainfall is a key factor contributing to slope failures in steep slopes, even in the absence of a groundwater table (Bonnard et al. 2008). Concentrated rainfall, as found by Pradhan et al. (2022), can trigger shallow landslides by reducing soil suction and subsequently, the shear strength of the soil. To include rainfall in the numerical analysis, it is important to take into account other contributing parameters such as hydraulic characteristics of soil (Cai and Ugai 2004), initial volume moisture content, rainfall intensity, and permeability of the soil, leading to a much more complex calculation. Considering this, the rainfall parameter is not included in the study.

To calculate the effects of rainfall on slope stability of road cut slopes, Pradhan et al. (2022) used a 17-h rainfall duration based on the results from their back analysis. The study established a correlation between rainfall duration and corresponding changes in the FoS, demonstrating that a longer duration of rainfall resulted in a greater reduction in FoS, and an increase in rainfall duration from 5 to 17 h causes an additional drop in the FoS by approximately 10%. Therefore, the effect of rainfall can be incorporated into the study by reducing the obtained FoS in all scenarios by 25%, accounting for 17 h of rainfall duration in the correlation graph of Decrease in factor of safety v/s Rainfall duration (Fig. 7).

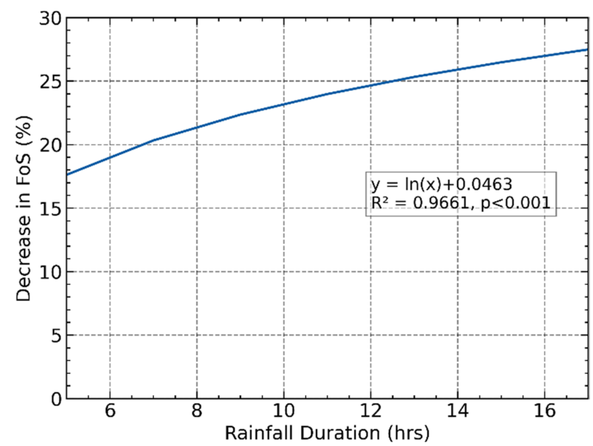

Fig. 7 Rainfall duration (h) v/s decrease in FoS (%), after Pradhan et al. (2022)

Vegetation and its effects on this study

To maintain brevity and minimize the influence of outliers, this study has not used vegetation parameters in the numerical analysis. However, the literature review indicates that vegetation strengthens soil stability in two ways—by changing the soil moisture regime and providing additional soil strength through roots (Löbmann et al. 2020). In addition, foliage intercepts rainfall and increases the roughness of the ground surface, thereby boosting the infiltration capacity of subsoil. Vegetation roots also bind soil particles and provide support to the up-slope soil mantle through buttressing (Mulyono et al. 2018). Nevertheless, though the vegetative cover is known to provide mechanical and hydrological reinforcement to slopes, extenuating factors such as droughts, plant lifecycle, forest fires, freeze–thaw cycles, and increased CO_2 emissions can compromise the reinforcement mechanisms (Bordoloi and Ng 2020). Moreover, the type of vegetation (herbaceous or woody), local environment, species mix, and plant health also affect the vegetative reinforcement performances (Löbmann et al. 2020). Due to these complexities, vegetative parameters were excluded from this study.

Implementation modality

From the above results, it is apparent that the FoS of the slopes subjected to rural roads is contingent on material properties (c, Φ, γ), and additionally on the geometric characteristics of the site. Consistent with published literature and common intuition, the FoS is observed to follow a downward trend as the steepness and cross-slope of excavation are increased. Moreover, the FoS also decreases with increasing steepness of the existing natural slope of the ground. The charts presented in the

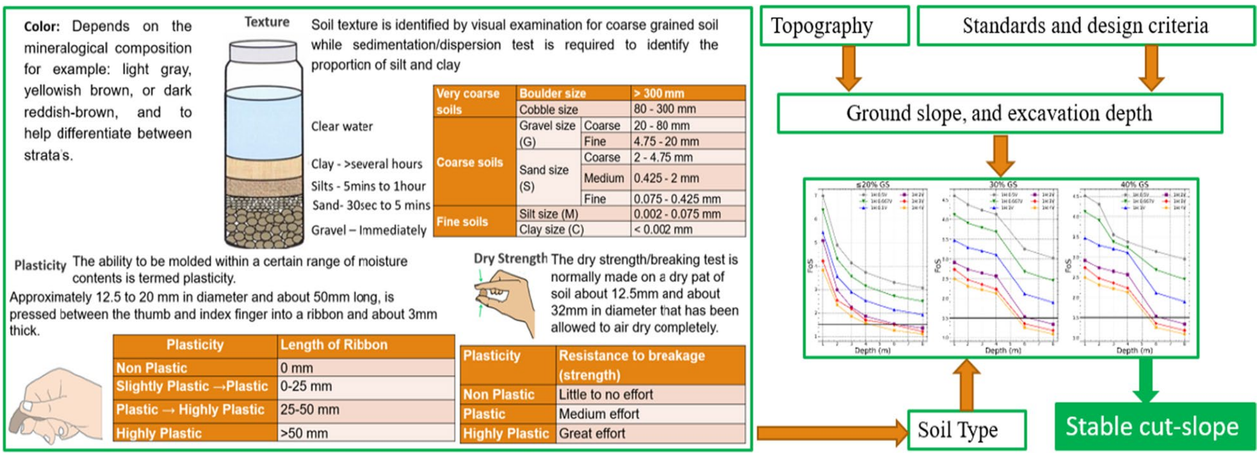

Fig. 8 General methodology proposed for selecting appropriate cut slope

results section of this paper can be used to determine the safe depth and slope of excavation for specific values of natural ground slope and field-identified soil parameters. The term safe in this context refers to an FoS of 1.5, which is considered the minimum desirable global safety value in several design guidelines under static conditions. We recommend that rural road practitioners use the methodology for field identification of soil parameters (Fig. 8) prescribed by the Nepal Reconstruction Authority, NRA (NRA 2021).

We recommend that rural road engineers follow the illustrated general framework before selecting the depth and slope of excavation.

Field validation

The field validation methodology described in the materials and methods section of this paper was used to perform a field-based slope stability assessment. The slopes were observed in the field and categorized into two groups, namely stable slopes and failed slopes. The FoS versus depth charts developed in this study were used to determine the FoS of the slopes. The data points obtained were then divided into two categories based on their alignment with the stability chart, i.e., pass and fail. The pass category included the slopes in which the observed field condition aligned with the stability charts. This means that slopes that were predicted to fail or not fail in the stability charts and had indeed failed or not failed in real life were classified as pass. Conversely, the opposite was classified as fail. The field assessment area includes representative slopes, as shown in Fig. 9. Figure 9a depicts a completely failed slope section. Figure 9b shows a partially failed, partially vegetated slope. Figure 9d shows another slope section where a gabion wall has been used as a mitigation measure. In addition, Fig. 9e, f illustrate a barren failed slope and a vegetated safe slope, respectively.

Two scatter plots were generated (Fig. 10) for the data points obtained from the field-based slope stability assessment. The x-axes of both plots represented the calculated FoS values, while the y-axis represented the data points, which were categorized into two groups: pass points and fail points, depicted in green and red respectively. The difference between the two scatter plots was that the FoS of the first plot (Fig. 10a) were not adjusted for rainfall parameters, while the FoS values in the second plot Fig. 10b) were reduced by 25% to adjust for rainfall parameters.

Results from validation study

The validation rates for each chart can be calculated by dividing the number of pass points by the total number of data points. For the former chart, the validation rate stands at 61%. For the latter chart, the validation rate stands at 65%. Though the validation rates for both charts are relatively low, the slightly better validation rate of the latter chart highlights the importance of taking rainfall into account for more accurate results. However, it is important to note that the methodology was still able to accurately predict the stability of the majority of slopes, indicating its future use in slope failure remediation and management.

The following key observations were obtained from the field validation:

1. In general, slopes with FoS higher than 1.5 were found to be stable in the field. Only four sections of the failed slopes had FoS greater than 1.5. This suggests that elements like drainage conditions and runoff-induced gully erosions, excluded in this study,

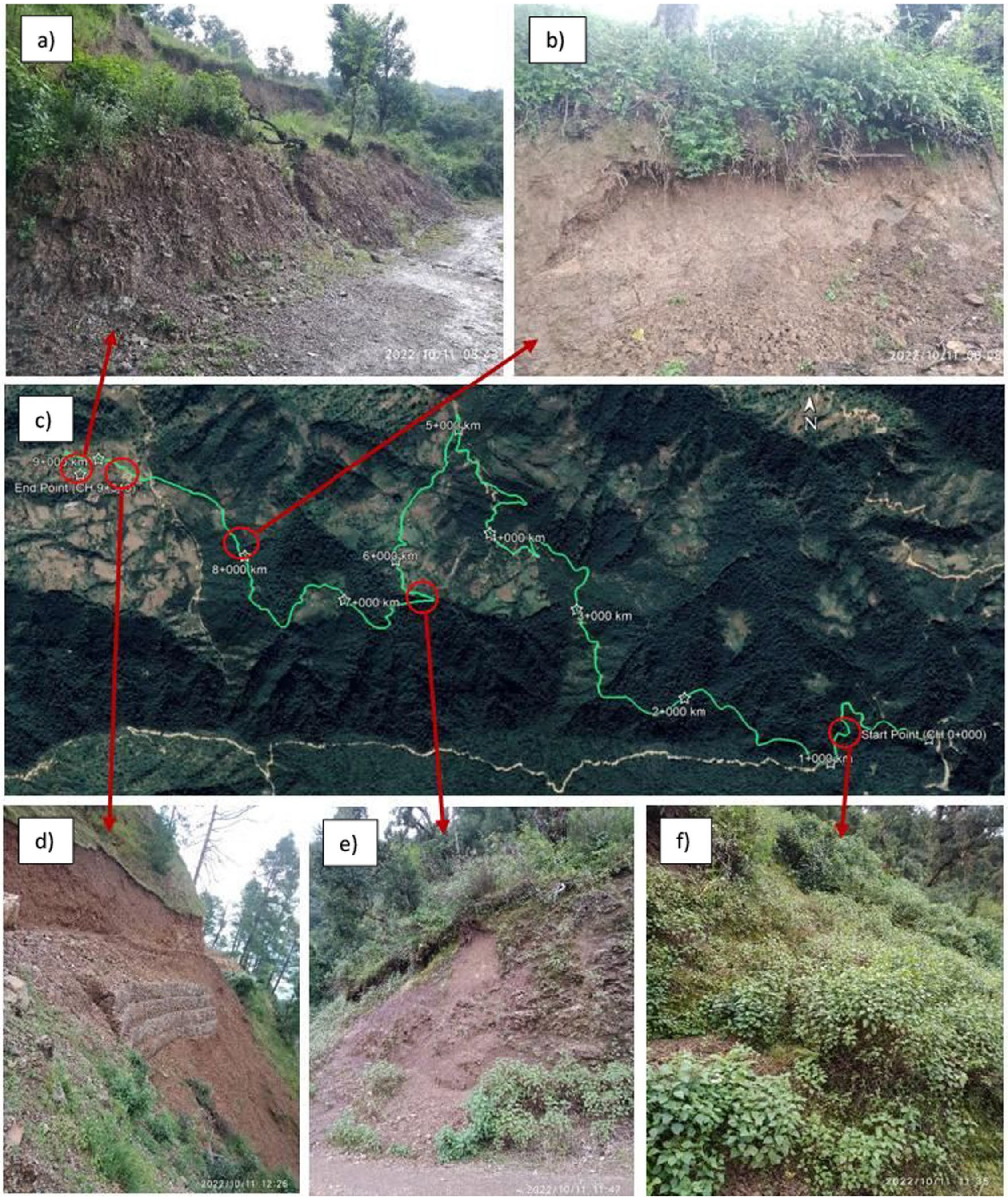

Fig. 9 Representative slope conditions of the Anarkholi-Bajkot-Khateda road

contribute to the failure of slopes considered safe in the design charts.

2. The FoS of the failed slopes falls between the values of 1 and 2, with 50% of failed slopes falling below the unsafe threshold of 1.5. Also indicates that factors not considered in the present study, such as drainage conditions and runoff-induced gully erosions, contribute to the failure of slopes deemed safe on the design charts.
3. Slopes with FoS less than 1.5 were found safe in many instances (approximately 40%), highlighting one of the key limitations, i.e., the effect of vegetation on slope stability. Five of the six stable slopes deemed unsafe by the assumptions and model of this study

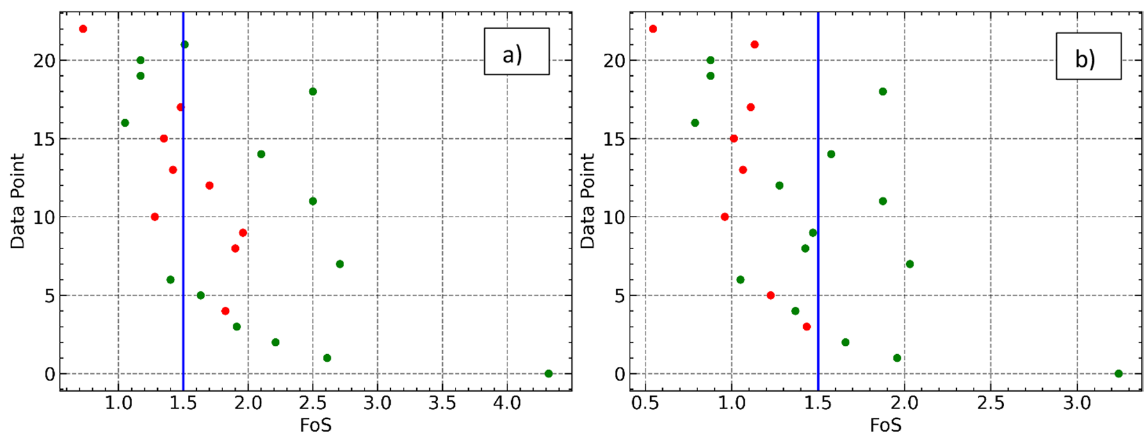

Fig. 10 Field validation scatter plots: **a** before rainfall parameter adjustment, **b** after rainfall parameter adjustment

are in densely vegetated areas (Fig. 10). Three of the five slopes are covered by dense woods dominated by *Quercus leucotrichophora*, an oak species native to Nepal's Sudurpaschim Province. The effects of root retention and passive root reinforcement must thus be investigated further to provide considerably more extensive and precise results.

Conclusions

The study sought to address the issue of poor rural road construction in Nepal due to a lack of expertise and clear guidelines, resulting in frequent mass movements in the Himalayas. A systematic slope excavation method for local road construction in Nepal was developed by evaluating the FoS for different cut slopes and cut heights in different soil types and cross/hill slopes using the Morgenstern–Price method. Additionally, user-friendly charts depicting the safe depth of excavation were created, and a method for putting the charts into use was proposed by modifying the soil identification procedure developed by the Nepal Reconstruction Authority in 2021.

Based on numerical simulation and analysis, we have highlighted the urgent need for rural road excavation guidelines. The present guidelines enacted by the DoR and intended for the SRN are not only practically unviable but also economically unfeasible to implement on rural roads.

It is critical to emphasize that the FoS values are approximations for ideal slope conditions and do not take factors such as site-specific topographical and hydrological features into account in the numerical analysis portion of the study. The results, however, are a good starting point for developing stability charts tailored specifically for low-cost local roads.

In conclusion, the study emphasizes the critical need for rural road excavation guidelines, as well as the importance of capacity building and upgrades to the existing institutional framework, to discourage the construction of unscientifically constructed rural roads. To build sustainable roads in the Himalayan region, clear guidelines for the excavation slope regarding soil type, excavation depth, and ground slope are required. The study's findings would benefit all three levels of the Nepalese government and contribute to a more scientific future for slope stability analyses.

The main findings are summarized as follows:

1. For GS values of 40%, 50%, and 60%, FoS is independent of cut slopes for small cut depths for all six scenarios.
2. Cohesion is a very important factor in slope stability, as it increases FoS gradually with an increase in cut slopes in accordance with the ground slopes.
3. High Plasticity Clay is the most stable soil type when subjected to excavation and coarse-graded sands are the weakest and are highly prone to failure.
4. The ground slopes play a vital role in the stability of the slope as they are the most sensitive to changes in the depth of the cut and soil types.
5. The field validation rate of the present study based on a field assessment currently stands at 61% before rainfall adjustment and 65% after rainfall adjustment.
6. The assessment of the effects of hydrological factors such as surface drainage and runoff accumulation zones is crucial to further calibrate the model devised in the study.
7. The assessment of the effects of vegetation on the overall stability of slopes is important to further improve the validation rate of the model presented in the study.

Acknowledgements
The authors thank the Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Lalitpur, Nepal, for providing all the facilities and encouragement throughout this work.

Author contributions
The first and second authors carried out the numerical modeling, analysis, and drafting of the manuscript. The third author conducted the field study and offered finalization and correction of the models. The fourth author contributed to the research concept, editing, and structural review. All authors read and approved the final manuscript.

Funding
Not applicable.

Availability of data and materials
The datasets utilized and analyzed during the current study are available from the corresponding author at a reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 24 January 2023 Accepted: 23 March 2023
Published online: 31 March 2023

References
Acharya B, Karmacharya B, Meyer WP (1999) Green roads in Nepal. German Technological Cooperation (GTZ), Eschborn
Bonnard C, Tacher L, Beniston M (2008) Prediction of landslide movements caused by climate change: modelling the behaviour of a mean elevation large slide in the Alps and assessing its uncertainties. In: Chen Z, Zhang J, Li Z, Wu F, Ho K (eds) Landslides and engineered slopes. From the past to the future. CRC Press, Boca Raton, pp 217–227. https://doi.org/10.1201/9780203885284-c13
Bordoloi S, Ng CWW (2020) The effects of vegetation traits and their stability functions in bio-engineered slopes: a perspective review. Eng Geol 275:105742. https://doi.org/10.1016/j.enggeo.2020.105742
Bureau of Indian Standards (1997) Indian standard: retaining wall for hill area-guidelines. Government of India, Bureau of Indian Standards, New Delhi
Cai F, Ugai K (2004) Numerical analysis of rainfall effects on slope stability. Int J Geomech 4:69–78. https://doi.org/10.1061/(ASCE)1532-3641(2004)4:2(69)
Chen WF, Giger MW, Fang HY (1969) On the limit analysis of stability of slopes. Soils Found 9:23–32. https://doi.org/10.3208/sandf1960.9.4_23
Department of Local Infrastructure Development and Agricultural Roads (2014) Nepal rural road standards, 2071. Department of Local Infrastructure Development and Agricultural Roads, Government of Nepal
DoR-Department of Roads (2003) Guide to road slope protection works. Government of Nepal, Ministry of Physical Infrastructure and Transport, Department of Roads, Kathmandu
DoR-Department of Roads (2014) Nepal road standard 2070. Government of Nepal, Ministry of Physical Infrastructure and Transport, Department of Roads, Kathmandu
DoR-Department of Roads (2018) Norms for rate analysis of road and bridge works. Department of Roads, Ministry of Physical Infrastructure and Transport, Government of Nepal. https://dor.gov.np/qrdc/publication/1qrdc-guidelines-standard-specifications-codes-and-norms/norms-for-works-road-and-bridges
Fredlund DG, Morgenstern NR, Widger RA (1978) The shear strength of unsaturated soils. Can Geotech J 15:313–321. https://doi.org/10.1139/t78-029
Froude MJ, Petley DN (2018) Global fatal landslide occurrence from 2004 to 2016. Nat Hazards Earth Syst Sci 18:2161–2181. https://doi.org/10.5194/nhess-18-2161-2018
GeoSlope (2018) GeoStudio slope/W. Computer Software
Hearn GJ, Shakya NM (2017) Engineering challenges for sustainable road access in the Himalayas. QJEGH 50:69–80. https://doi.org/10.1144/qjegh2016-109
Hoek E, Brown ET (2019) The Hoek–Brown failure criterion and GSI—2018 edition. J Rock Mech Geotech Eng 11:445–463. https://doi.org/10.1016/j.jrmge.2018.08.001
ITAD (2017) Nepal rural access programme—monitoring, evaluation and learning component: reality check approach baseline report. ITAD, Hove
Ives JD, Messerli B, Strong MF (2003) The Himalayan dilemma: reconciling development and conservation, 1st edn. Taylor and Francis, Abingdon
Jennings JEB, Burland JB (1962) Limitations to the use of effective stresses in partly saturated soils. Géotechnique 12:125–144. https://doi.org/10.1680/geot.1962.12.2.125
Klatzel F (2000) Green roads: building environmentally friendly, low maintenance rural roads through local participation. GTZ Food for Work, Nepal
Lawrence C, Hearn G (1997) ORN 16: Principles of low cost road engineering in mountainous regions, with special reference to the Nepal Himalaya. Transport Research Laboratory (TRL) Overseas Road Note 16. https://webarchive.nationalarchives.gov.uk/20090609164828/http://www.transport-links.org/transport_links/publications/publications_v.asp?id=713&title=ORN16+PRINCIPLES+OF+LOW+COST+ROAD+ENGINEERING+IN+MOUNTAINOUS+REGIONS
Lawrence C, Hearn G (2002) Overseas road note 16: principles of low-cost road engineering in mountainous regions, with special reference to the Nepal Himalaya
Löbmann MT, Geitner C, Wellstein C, Zerbe S (2020) The influence of herbaceous vegetation on slope stability—a review. Earth Sci Rev 209:103328. https://doi.org/10.1016/j.earscirev.2020.103328
McAdoo BG, Quak M, Gnyawali KR, Adhikari BR, Devkota S, Rajbhandari PL, Sudmeier-Rieux K (2018) Roads and landslides in Nepal: how development affects environmental risk. Nat Hazard 18:3203–3210. https://doi.org/10.5194/nhess-18-3203-2018
Minnesota Department of Transportation (2007) MnDOT pavement design manual. Minnesota Department of Transport, St. Paul
Morgenstern NR, Price VE (1965) The analysis of the stability of general slip surfaces. Géotechnique 15:79–93. https://doi.org/10.1680/geot.1965.15.1.79
Mulmi AD (2009) Green road approach in rural road construction for the sustainable development of Nepal. J Sustain Dev. https://doi.org/10.5539/jsd.v2n3p149
Mulyono A, Subardja A, Ekasari I, Lailati M, Sudirja R, Ningrum W (2018) The hydromechanics of vegetation for slope stabilization. IOP Conf Ser Earth Environ Sci 118:012038. https://doi.org/10.1088/1755-1315/118/1/012038
NAVFAC (1986) NAVFAC design manual 72—foundations and earth structures. United States Navy, Naval Facilities Engineering Systems Command, Washington
NRA-National Reconstruction Authority, & NDRRMA - National Disaster Risk Reduction and Management Authority (2021) Manual for hands-on training to engineers on slope stabilization techniques, p 238. Project Management Unit, Earthquake Housing Reconstruction Project, National Reconstruction Authority
Petley DN, Hearn GJ, Hart A, Rosser NJ, Dunning SA, Oven K, Mitchell WA (2007) Trends in landslide occurrence in Nepal. Nat Hazards 43(1):23–44. https://doi.org/10.1007/s11069-006-9100-3
Pradhan S, Toll DG, Rosser NJ, Brain MJ (2022) An investigation of the combined effect of rainfall and road cut on landsliding. Eng Geol 307:106787. https://doi.org/10.1016/j.enggeo.2022.106787
Rankin KN, Sigdel TS, Rai L, Kunwar S, Hamal P (2017) Political economies and political rationalities of road building in Nepal. St Nepali Hist Soc 22:43–84
Robson E, Agosti A, Utili S, Milledge D (2022) A methodology for road cutting design guidelines based on field observations. Eng Geol 307:106771. https://doi.org/10.1016/j.enggeo.2022.106771
Scott Wilson (2003) Landslide risk assessment in the rural sector: Guidelines on best practice: Remote sensing, landslide hazard and risk mapping, land use planning and management, route corridor engineering. Scott Wilson Kirkpatrick & Co Ltd. https://assets.publishing.service.gov.uk/media/57a08d0740f0b652dd0016f4/R7815-ADD017_col.pdf
Singh BP (2018) From nowhere to nowhere: haphazard road construction is raging the Nepali countryside. Nepali Times

Sudmeier-Rieux K, McAdoo BG, Devkota S, Rajbhandari PCL, Howell J, Sharma S (2019) Invited perspectives: mountain roads in Nepal at a new crossroads. Nat Hazards Earth Syst Sci 19:655–660. https://doi.org/10.5194/nhess-19-655-2019
Sutejo Y, Gofar N (2015) Effect of area development on the stability of cut slopes. Procedia Eng 125:331–337. https://doi.org/10.1016/j.proeng.2015.11.071
Taylor DW (1937) Stability of earth slopes. J Boston Soc Civ Eng 24:197–247
UNEP: United Nations Environment Programme, UNDP: United Nations Development Programme, & Government of Nepal, Ministry of Local Development (2011) Economic Analysis of Local Government Investment in Rural Roads in Nepal. https://wedocs.unep.org/20.500.11822/26511

Publisher's Note