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Numerical Evaluation of Post-Earthquake Stability and Rehabilitation of Mountain Trails 'Unnat Goreto' in Gorkha and Rasuwa Districts, Nepal

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Abstract: This study investigates the stability of mountain trails (locally known as *Unnat Goreto*) that were rehabilitated in highly affected communities of Gorkha and Rasuwa Districts following the 2015 Mw 7.8 Gorkha Earthquake in Nepal. The stability of critical trail sections was analyzed using the 2D Finite Element Method (FEM) in Rocscience Phase2 software. This paper presents the stability assessment of one representative critical section from each trail, both rehabilitated in 2017. Stability was evaluated under both best- and worst-case scenarios using the Strength Reduction Method (SRM) based on the Mohr–Coulomb and Hoek–Brown failure criteria.Results indicate that the slope is stable under static conditions and marginally safe under a pseudo-static horizontal seismic coefficient (EQx) of 0.1g, but becomes unstable under higher seismic loading for the trail in Gorkha District. In contrast, the trail in Rasuwa District shows relatively higher stability. The soil-bioengineering slope stabilization techniques applied immediately above and below the trail sections significantly enhance the factor of safety. Additionally, dry stone walls constructed below the trail as retaining structures contribute substantially to slope stability, with their effectiveness varying by wall type (Type 1-3). The analysis also incorporates the influence of mule loads, track components, and stabilization measures. Overall, the study emphasizes the importance of integrating geotechnical design with bioengineering and appropriate structural interventions to ensure the long-term stability and functionality of rehabilitated mountain trails in seismically active, mountainous regions.

Keywords: ***Mule track, Stability analysis, Safety factor, Finite Element Method, Earthquake***

Introduction

This research focuses on the stability analysis of trails in the earthquake-affected areas of Gorkha and Rasuwa Districts that were rehabilitated following the Mw 7.8 Gorkha Nepal Earthquake of 2015. These trails were primarily constructed in regions inaccessible to motorable transport, where existing routes were unsafe and unstable. The study is based on the field-level implementation of trail rehabilitation projects carried out by the National Reconstruction Authority (NRA), Government of Nepal (GoN), which was established in 2015 after the earthquake. The NRA prioritized the construction of safe trails in the most severely affected districts. The construction period spanned from December 2016 to November 2017.

The trail projects were implemented in two districts - three Village Panchayats (VPs) of Gorkha (Manbu, Kashigaun, and Kerauja) and four VPs of Rasuwa (Haku, Saramthali, Yarsa, and Bhorle). Major components of the projects included trail rehabilitation, standardization and upgrading of existing routes, footbridge construction, and establishment of rest areas, and awareness activities for hazard-prone communities, as summarized in Table 1. Figure 1 presents a Google Earth image of the Gorkha trail extending from Dhunchet Majhgaon to Hulchuk village, covering approximately 70 km. Similarly, Figure 2 and Figure 3 illustrate the two trail loops in Rasuwa District — Loop 1 from Malum to Nesing and Loop 2 from Sarsung to Rajang villages — spanning a total length of about 55 km.

Figure 4 provides an overview of the trail construction process, including slope stabilization works, gabion breast walls, and trail construction on steep slopes. Figure 5 and Figure 6 show field-level implementations with different dry stone wall sections designed according to the available slope gradient. Figure 7 and Figure 8 present typical examples of critical trail sections in Gorkha District, characterized by vertical cliffs, narrow passages, and exposed hard rock formations. Figure 9 and Figure 10 illustrate trail conditions before and after the earthquake, showing how the reconstructed trails reduce slope gradient, slow surface runoff, and enhance safety and comfort.

The trail section models were developed based on the identification of critical stretches using Google imagery. Previous studies and guidelines on safe and stable trail construction include USDA (1984), Charles

et al. (2001), Minnesota Guideline (2006), and Trail Design Guidelines (2009). However, based on the literature reviewed for this study, few studies in Nepal have specifically addressed the numerical stability of mountain trails, making this research a novel contribution in this field.

Nepal, being predominantly mountainous, has extensive areas covered by hills and rugged terrain. In many remote villages, constructing motorable roads is not feasible due to safety concerns, high costs, and challenging topography. Therefore, mule trails remain a practical and sustainable transportation solution in such regions.

With this background, the objective of this study is to analyze the stability of mule trails constructed in highly affected communities — particularly in the epicentral zones of the 2015 Gorkha earthquake — within Gorkha and Rasuwa Districts. The stability evaluation was performed using a two-dimensional finite element-based program, Rocscience Phase2 (Rocscience, 2012). A homogenization approach was adopted to incorporate the root-reinforcing effects in the slope. Field identification of soil and rock types was used to estimate geotechnical parameters and develop material models. The effectiveness of slope stabilization measures was then assessed in critical trail sections under both static and seismic conditions.

Although this is a case-based study, the approach can be replicated in other parts of Nepal. Given that thousands of remote settlements still rely on mule trails, such trails will likely remain an essential means of transportation for several decades. Hence, ensuring the stability and safety of these trails is both technically and socioeconomically justified.

Table 1 presents the key components of mule trail construction carried out in the earthquake-affected areas of Gorkha and Rasuwa Districts. A total of 125 km of trails were constructed, with 70 km in Gorkha and 55 km in Rasuwa. The project included the installation of nine foot or truss bridges—five in Gorkha and four in Rasuwa—covering a combined span of 180 meters. To support pedestrians, 15 rest areas or sheds were built, comprising eight in Gorkha and seven in Rasuwa. Safety measures involved the installation of approximately 840 meters of handrails and handholds in critical sections. Furthermore, 8,000 square meters of bioengineering works were implemented on landslide-prone slopes, along with 750 meters of geohazard mitigation structures to enhance the stability and resilience of the trail network.

These works not only restored connectivity but also strengthened the resilience of local communities in the earthquake-affected mountains. The integration of structural measures and bioengineering solutions improved trail safety, accessibility, and sustainability, while the rest areas enhanced traveler comfort. Overall, the project demonstrates a model of resilient and environmentally sensitive trail rehabilitation in Gorkha and Rasuwa.

Table 1, Mule Trail construction in the affected area in Gorkha and Rasuwa Districts

S. No.	Major components of the Trail construction	Detail
1	Trails (km)	125 (Gorkha: 70, Rasuwa: 55)
2	Foot bridge/truss bridge (Total Nos. and Total span in meter)	9 (Gorkha: 5, Rasuwa: 4), 180
3	Rest areas/pedestrian rest shed (Nos.)	15 (Gorkha: 8, Rasuwa: 7)
4	Handrail and handholds in critical sections	840 m
5	Bioengineering works on landslides	8,000 sq. m
6	Geohazard mitigation works	750 m

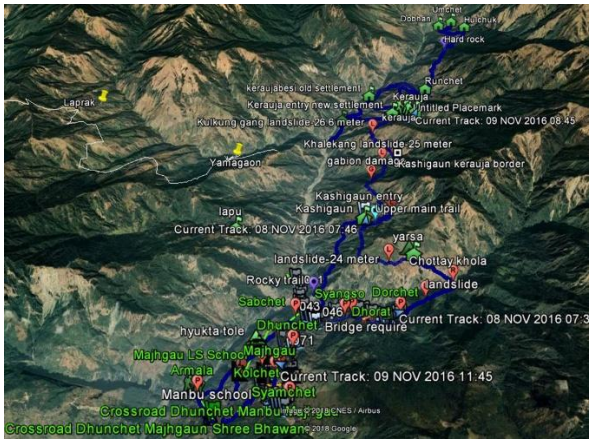


Figure 1, A resilient rehabilitation of trails in highly affected communities of Gorkha Districts

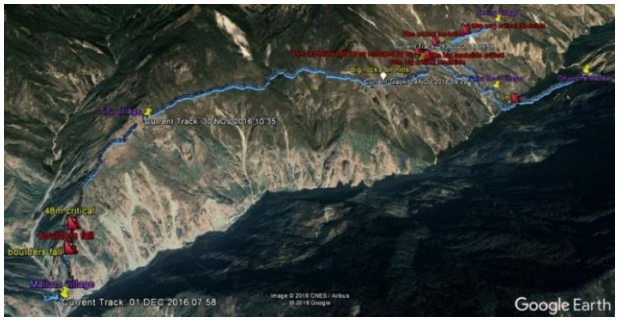


Figure 2, A resilient rehabilitation of trails in highly affected communities of Rasuwa Districts (loop-1)



Figure 3, A resilient rehabilitation of trails in highly affected communities of Rasuwa Districts (loop-2)



Figure 4, General overview of trail construction: (a) Trail with side slope stabilization work, (b) People's participation in trail construction, (c) Typical Gabion works for Breast wall and (d) Trail construction in the steep slope



Figure 5, Field level implementation of trails: (a) Trail with no side slopes, (b) Trail with one side slope. Employed standard dry wall section of Type-2 (mild) and (c) Trail with one side slope (steep). Employed standard dry wall section of Type-3 (steep)



Figure 6, Field level implementation of trails: (a) Trail with Retaining wall and (b) Trail with both Retaining and Breast walls

Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10 collectively highlight the comprehensive approach adopted for resilient trail rehabilitation in the earthquake-affected mountain regions. The designs emphasize terrain adaptability, slope stability, and user safety through appropriate structural and bioengineering measures. By integrating local materials, traditional construction techniques, and modern engineering practices, the project not only restored vital mobility routes but also promoted sustainable development and community ownership in Gorkha and Rasuwa Districts. These reconstructed trails now serve as safe, reliable, and climate-resilient pathways connecting remote settlements and supporting local livelihoods.



Figure 7, Critical sections of Trail (due to vertical cliffs, narrow passage and hard rocks): (a) Closure view of unstable Trail and (b) Overall view of unstable Trail



Figure 8, Widening and stabilizing works at critical sections of Trail (due to vertical cliffs, narrow passage and hard rocks): (a) Widening of existing unstable Trail and (b) Closure view of Rock drilling works



Figure 9, Before and after the construction of Trail, that helps to reduce effective grade and slow water down

and the trail should be comfortable, safe and intact: (a) Before the construction and (b) After the construction



Figure 10, Before and after the construction of dry-stone wall (Gabion walls) for debris fall protection and proper drainage system to ensure longevity of the trails: (a) Before at section-1, (b) After at section-1, (c) Before at section-2 and (d) After at section-2

Stability of trails

The designs of the Trails are based on past practices, experience and reference documents. The Department of Local Infrastructure Development and Agricultural Road norms (DoLIDAR, 2010) to construct Trails are strictly followed by NRA. The Trail construction activities undergo strict engineering procedures, e.g. layout of structures, proper drainage system, proper cut slope, etc. The every kilometer of trail is prepared in the following manner: 1) Minimum width of 1.5m, 2) Extensive erosion control through dry walls and skin walls, 3) Provision of longitudinal and cross drainage structures, 4) Stone balancing approach applied to maximize locally available stones, 5) Geological and Geotechnical assessments to minimize and control hazards, 6) Standard template of dry walls with sectional area in sq. meters are employed and 7) Typical cross section with design, ground level and structure are prepared. These are prepared based on the stability evaluation of the existing Trails. The cross-sectional design and field level implementation (dimensions in meter) of Trails are differed from place to place.

Different types of Tail components were designed and implemented for the sustainability of the trails. The major components of Trails provided were: 1) Flag stone paving, 2) Stone soling, 3) Drainage structures, 4) Retaining and skin walls and 5) Cross drainage structures (scoopers). Besides that, some supplementary structures provided in Trails were: 1) Foot bridges: 9 for Gorkha and Rasuwa, designs based on DoLIDAR/TBSU norms (contractor built), 2) Hand rails: ISMC 75 channel sections and GI pipes used for additional safety and 3) Rest areas: Pedestrian sheds for protection and rest. In addition to these, intensive bioengineering works were planned for post monsoon activities. Bioengineering and slope stabilization works involved were: 1) Cut and fill slope stabilization works practiced maintaining cut and fill slopes, 2) Providing structures as skin walls and toe walls, 3) Landslide debris cleared and minimum passage of 1.5m maintained in landslide areas. Geological and Geo-technical assessment of 41 landslides across 125 kms of trails were carried out and recommendations had been made accordingly. The Trail encountered some critical section such as vertical cliffs, narrow passage, hard rocks, Rock fall, Slope failures and landslides. Table 2 and 3 listed out all 41 landslides in the Trails of both Gorkha and Rasuwa Districts. To minimize the threat, post monsoon activities were planned. A safe cut slope was provided with the help of drilling machines/jack hammers. The mitigation model of landslide slope at critical stretches of Trails can be prepared based on Popescu (2001) and DOR (2007).

Table 2, Landslide at Trails in Gorkha District

S. No.	Landslide Name/Critical Strech (m)	Latitude, Longitude Coordinate (Deg.-Min.-Sec.)
1	Landslide prone zone-1, 30	28-81-41.17N, 84-52-27.83E
2	Biba Kholsa, 50	28-11-43.09N, 84-54-15.24E
3	Dijet, 111.1	28-11-48.22N, 84-54-10.57E
4	Banglang, 86	28-11-49.74N, 84-54-9.45E
5	Khalekang, 25	28-12-50.45N, 84-53-51.61E
6	Kulkung Gang, 26.6	28-13-28.46N, 84-53-32.36E
7	Keranja, 25	28-14-18.29N, 84-53-59.73E
8	Landslide zone-2, 20	28-8-39.37N, 84-52-53.82E
9	Landslide zone-3, 25	28-8-56.66N, 84-52-51.24E
10	Landslide zone-4, 20	28-10-20.42N, 84-55-5.48E
11	Landslide near Yarsa School, 24	28-10-45.28.28N, 84-54-22.88E

Tables 2 and Table 3 mentioned 11 landslide sites in Gorkha and 29 in Rasuwa, several damaged by the 2015 Gorkha earthquake. Their coordinates support precise monitoring and mitigation planning along the reconstructed trails. Figure 11 illustrates the stability condition of the trail near Hyukta Tole in Gorkha District, where a 30 m critical stretch has been affected by landslide.



Figure 11, Stability of trails near to Hyukta Tole in Gorkha Districts (30 m critical stretch due to landslide)

Table 3, Landslide at Trails in Rasuwa District

S. No.	Trail	Landslide Name/Critical Strech (m)	Latitude, Longitude Coordinate (Deg.-Min.-Sec.)
1		Landslide near to cross road Lumbadanda, 12.5	28-6-22.41N, 85-15-4.93E
2	Loop-1	Landslide zone-1, 10	28-6-21.37N, 85-15-6.66E
3		Landslide zone-2, 20	28-6-24.34N, 85-15-14.42E
4		Landslide enlarged by 2015 Gorkha EQ, 91	28-7-7.63N, 85-15-47.91E
5		Landslide zone-3, 85	28-7-28N, 85-15-51.42E
6		Landslide zone-4, 88	28-7-7.33N, 85-15-55.22E
7		Landslide zone-5, 93	28-7-10.09N, 85-15-57.39E
8		Landslide zone-6, 76	28-7-25.10N, 85-16-4.90E
9		Landslide near to Nesing village, 15	28-7-35.76N, 85-16-27.45E
10		Landslide zone-7, 118	28-7-37.43N, 85-16-30.80E
11		Landslide zone-8, 15	28-7-11.28N, 85-16-4.05E
12		Landslide zone-9, 40	28-7-5.64N, 85-16-21.50E
13	Loop-2	Landslide zone-1, 28	28-7-2.55N, 85-16-31.89E
14		Landslide zone-2, 70	28-0-55.92N, 85-15-7.79E
15		Landslide zone-3, 102	28-1-10.58N, 85-15-7.86E
16		Landslide zone-4, 20	28-1-18.80N, 85-15-12.13E
17		Landslide zone-5, 50	28-1-20.12N, 85-15-45.90E
18		Landslide zone-6, 25	28-0-21.43N, 85-15-26.18E
19		Landslide near to Parchyang, 8	28-0-46.82N, 85-16-28.12E
20		Landslide zone-7, 15	28-1-4.59N, 85-16-28.91E
21		Landslide near to 2 alternative trails reaching to Ghichet, 12	28-0-28.98N, 85-16-47.13E
22		Landslide prone zone-8, 15	28-0-26.05N, 85-16-54.56E
23		Landslide near to Ghichet, 7	28-0-19.68N, 85-17-22.65E
24		Landslide prone zone-9, 55	28-1-3.48N, 85-18-41.33E
25		Landslide prone zone-10, 15	28-0-57.61N, 85-18-49.14E
26		Landslide prone zone-11, 12	28-0-44.89N, 85-18-58.59E
27		Landslide prone zone-12, 10.3	28-2-7.31N, 85-18-10.63E
28		Landslide prone zone-13, 25	28-2-3.41N, 85-18-16.96E
29		Landslide prone zone-14, 2 landslides near to Simbandi, 27.2 and 30	28-2-13.82N, 85-18-42.09E

Figures 11, Figure 12, Figure 13 and Figure 14 illustrate representative critical trail sections affected by landslides in Gorkha District, showing the location and extent of vulnerable stretches identified during field investigation. Figures 15, Figure 16, Figure 17, Figure 18, Figure 19 and Figure 20 illustrate the stability conditions of critical trail sections affected by landslides in Gorkha and Rasuwa Districts. The identified stretches, ranging from 5 to 118 meters, include major sites such as Majhgau, Kolchet, Yarsa, Chottay Khola, Lumbadanda, Thulo Haku, Nesing, Haku Besi, and Ghurmu. These figures highlight key areas requiring continuous monitoring and stabilization to ensure safe and resilient trail connectivity. These figures demonstrate the varying severity and distribution of landslide-affected sections along the trails, emphasizing the need for tailored stabilization measures. By documenting critical stretches with precise lengths and locations, the study provides a clear basis for designing site-specific interventions, such as slope reinforcement, bioengineering, and drainage improvements, to enhance trail safety and long-term resilience in the earthquake-prone mountain regions of Gorkha and Rasuwa.



Figure 12, Stability of trails near to Biba Kholsa in Gorkha Districts (50, 111.1 and 86m critical stretches due to Biba Kholsa, Dijet and Bangland landslides)

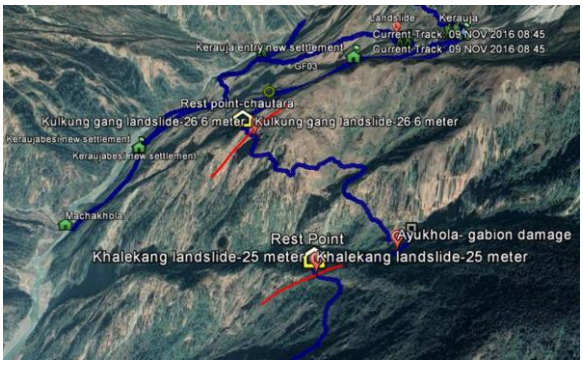


Figure 13, Stability of trails near to Khalekang and Kulkung gang landslides in Gorkha Districts (25 and 26.6m critical stretches due to Khalekang and Kulkung landslides)



Figure 14, Stability of trails near to Kerauja landslide in Gorkha Districts (25m critical stretches due to landslide)



Figure 15, Stability of trails near to Majhgau and Kolchet landslide in Gorkha Districts (20-25m critical stretches due to landslides)



Figure 16, Stability of trails near to Yarsa and Chottay Khola landslide in Gorkha Districts (24 and 20m critical stretches due to landslides)

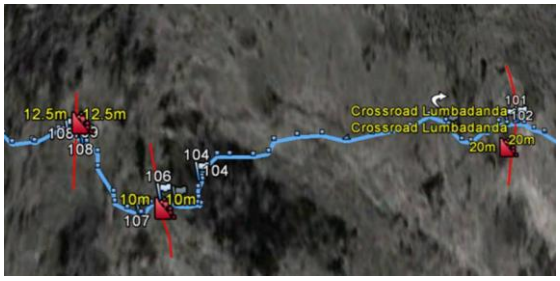


Figure 17, Stability of trails under loop-1 near to Crossroad Lumbadanda landslide in Rasuwa Districts (12.5, 10 and 20m critical stretches due to landslides)



Figure 18, Stability of trails under loop-1 near to Thulo Haku, Nesing Village and Haku Besi village landslide in Rasuwa Districts (88, 91, 76, 118, 15, 40 and 28m critical stretches due to landslides)



Figure 19, Stability of trails under loop-1 near to Haku Besi village (near to Dhunche Bazar) landslide in Rasuwa Districts (5m critical stretch due to landslide)



Figure 20, Stability of trails under loop-2 near to Ghurmu landslide in Rasuwa Districts (70, 102, 20 and 50m critical stretches due to landslides)

Figure 21, Figure 22, and Figure 23 illustrate additional critical trail sections along Rasuwa Loop-2, including the areas around Parchyang, Ghichet, Sangue, Sanguel and Simbandi.



Figure 21, Stability of trails under loop-2 near to Parchyang and Ghichet landslides in Rasuwa Districts (8, 12, 15 and 7m critical stretches due to landslides)



Figure 22, Stability of trails under loop-2 in between Ghichet and Sangue in Rasuwa Districts (55, 15 and 12m critical stretches due to landslides)

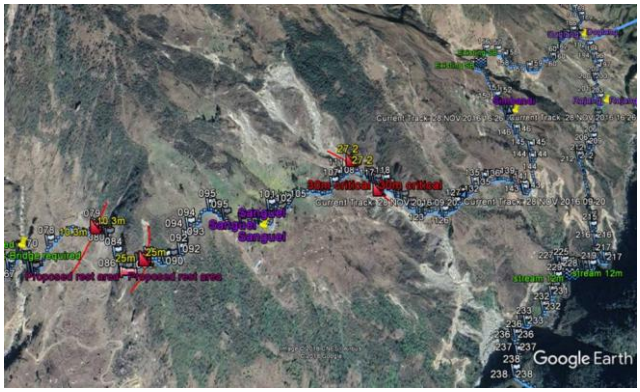


Figure 23, Stability of trails under loop-2 near to Sanguel, Simbandi in Rasuwa Districts (10.3, 25 and 30m critical stretches due to landslides)

Material and method

The soil/rock slope stability analysis is carried out using a finite element formulation provided in the Rockscience Phase2 (Rocscience, 2012). The debris and Rocks in the slopes are modeled as a continuum interface using 2D, plane strain problem. The discontinuities are represented as an interface element in between the Rock wall. The shear strength reduction technique is employed to explore stability of landslide slopes. This method is fully automated and used either Mohr-Coulomb or Hoek-Brown strength parameters. Finite element divide body into small element of 6 noded triangle. Displacement within the element is related to displacement at nodes through shape function. Transmission of internal forces between the edges of adjacent elements is represented by interactions at the nodes of the elements. Fixed boundary conditions are assumed along the lateral side and base of the model such that the displacement is restrained in both the x and y directions. The slope face is kept free. In the loading step, each FE is given both an initial stress and a body force (self-weight). The initial vertical stress is estimated from the weight of the material above the element. Phase2 automatically determines the ground surface above the element and the stress due to the material above the element. The horizontal to- vertical stress ratio σ_H / σ_V is kept as 1.0 according to Pal et al. (2012).

Strength reduction technique is employed here to explore critical safety factor. In Mohr–Coulomb and Hoek-Brown material model, the factored shear strength parameters C_f and ϕ_f are calculated as per Eq. (1) and (2) below.

$$C_f = \frac{C}{SRF} \qquad (1)$$

$$\varphi_f = \tan^{-1}\frac{Tan\varphi}{SRF} \qquad (2)$$

Where SRF is the 'strength reduction factor (SRF).' This method is referred to as the 'shear strength reduction (SSR) technique (Matsui and San, 1992). Four-nodded quadrilateral zero thickness element is used here as a joint element. 1D finite element is designed to simulate shear and normal displacements in the interfaces. The element was originally developed by Goodman et al. (1968). The undulations and asperities on a natural joint surface have a significant influence on its shear behavior. The shear strength in increased in the jointed surface due to shear resistance. Patton (1966) demonstrated the shear tests on saw-tooth specimens according to Eq. (3).

$$\tau = \sigma_n \tan(\varphi_b + i) \qquad (3)$$

The detail material models to explore stability of Mule Tracks in Gorkha District are presented according to Table 4 below. It contains both soil and rock properties. Soil properties are considered as per the field investigation and estimated the soil strength parameter according to Krahenbuhl and Wagner (1983). Similarly, Rock properties are estimated from the literatures such as Griffiths and Lane (1999), Hoek and Diederichs (2006) and Deere and Miller (1966). The step by step procedure to explore the stability of Mule Track includes: 1) Full enclosed boundary is created for the slope section generated from the slope profile in Rocscience Phase2, 2) The next step is adding material to the slope, 3) The failure criterion assigned are Mohr Coulomb for soil/debris and Generalized Hoek and Brown for fractured, jointed bedrock and joint failure criteria by Patton (1966), 4) Then discretization and meshing is done with 6 noded triangular element of 1500 numbers, 5) The boundary condition is fixed at sides and slope face is made free, 6) The gravity loading is assigned as initial effective stress and body force. The first horizontal to vertical stress is assigned as 1 and 7) On completing above procedure the slope stability analysis is ready to run.

Mule load analysis

The Mule load analysis is done accordingly as per Figure 24. An average Mule physical dimensions are presented in Table 5. The average mass (mav) of Mule and load carrying by Mule can be considered as 180+60=240kg (2354 kN weight). Considering an average value of acceleration (aav) of 1 m/s^2 of Mule while walking and neglecting the friction, the inertial force would be 240 N. Based on these calculations, the pulling forces at the flat surface would be, Fa=240/2=120N. For the inclined surface of 15 degrees, pulling force equals to 609N, Fa=240/2+609/2=424.5N, Similarly, for an inclined surface of 30 degrees, pulling force F_p=1177N, Fa=240/2+1177/2=708.5N.

Table 4, Material model *employed to explore the stability of Mule Tracks in Gorkha and Rasuwa Districts*

Material model for soil, according to Krahenbuhl and Wagner (1983)	
Material	Disintegrated debris slope (USCS soil type: CL)
Failure Criteria	Mohr-coulomb
Unit weight (kN/m^3)	17.5 (Gorkha), 18.0 (Rasuwa loop-1) and 19.0 (Rasuwa loop-2)
Elastic Properties	Griffiths and Lane (1999)
Modulus of elasticity (kPa)	10^5
Poisson ratio=0.3	0.3
Shear strength parameters	Field identification of soil types and suggested soil shear strength parameters according to Krahenbuhl and Wagner (1983)
Angle of friction, peak (Degree)	24 (Gorkha), 27.0 (Rasuwa loop-1) and 30.0 (Rasuwa loop-2)
Cohesion, peak (kPa)	10 (Gorkha), 10.0 (Rasuwa loop-1) and 15.0 (Rasuwa loop-2)
Material model for rock (Mule Track critical sections in Gorkha, Rasuwa loop-1 and 2)	
Material	Schist inters bedded with Phyllite
Failure Criteria	Generalized Hoek and Brown
Unit weight (kN/m3)	29
Elastic properties	
Modulus of elasticity	Hoek and Diederichs (2006)
Modulus of elasticity of intact rock (kPa)	54,000,000
Modulus of elasticity of rock mass (kPa)	29,306,428.2
Poisson ratio	0.3
Intact rock uniaxial compressive strength (UCS) according to Deere and Miller (1966), (kPa)	80,000
GSI (Marinos and Hoek, 2000) according to Cai et al. (2004)	60
mi according to Deere and Miller (1966)	7
Disturbance factor (No blasting), D	0
For joint	
Basic friction angle, ϕb (Degree)	20
Roughness angle, i (Degree)	15
Joint normal stiffness (GPa/m)	0.1
Joint shear stiffness (GPa/m)	0.01

The Mule has single hoof so it prefers walking on soft surfaces (soil). Stone soling (15 cm depth) up to 15% longitudinal gradient is not affected by Mules movement. Stairs in length with longitudinal gradient more than 30% are damaged more due to Mule movement. The rocks found in the trail construction area are mostly metamorphic rocks such as Phyllite and Schist. These rocks are weak and undergo breaking with pointed load. The best alternative is to use Meta sandstone and Phamatic Phyllite.

Figure 25 shows the standard template of dry wall along with a typical sectional view of the Trail that are implemented as per the analysis done. Similarly, Figure 26 shows a typical cross-sectional design and the field level implementation of trail.

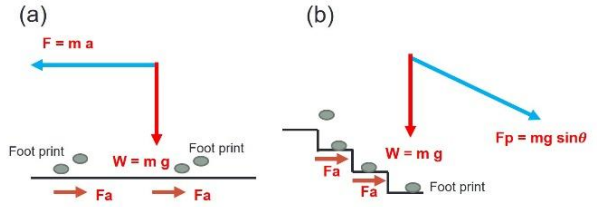


Figure 24, Mule load analysis: (a) Walking in the plain Trail and (b) Walking in the steep Trail

Table 5, Average Mule physical dimensions

S. No.	Parameters	Values
1	Length (m)	1.6-1.8
2	Weight (kg)	120-180
3	Load carrying capacity (kg) and load on each side (kg)	60, 30
4	Load in each leg (if distributed equally) (kg)	45-60
5	Diameter of hoof (cm)	7-9
6	Height of Mule (m)	1.1-1.3
7	Width of mule's waist without load (m)	0.5
8	Width of mule with load (Load pack+Mule body+Load pack)	1.1(0.3+0.5 +0.3)

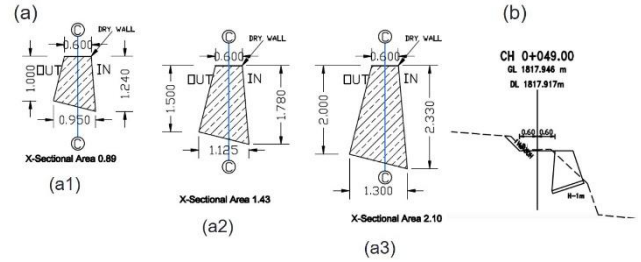


Figure 25, Standard template of dry wall along with typical sectional view of trail: (a) Type of dry stone wall along with sectional area (Sq. meters): (a1) Type-1 with sectional area of 0.89, (a2) Type-2 of sectional area of 1.43, (a3) Type-3 of sectional area of 2.10 and (b) Sectional view with Retaining wall

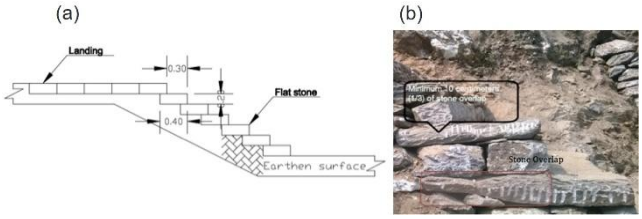


Figure 26, Typical cross-sectional design and field level implementation of trail: (a) Design drawing (dimensions in meter) and (b) Field implementation (Minimum 10 centimeters (1/3) of stone overlap)

Results and discussion

The summary of the computational results of landslide slope stability of 3 critical sections of mountain Trails in Gorkha and Rasuwa Districts of Nepal is presented in Table 6. The results are computed for different seismic coefficient along with dry stone wall and bio-engineering layer. The construction of Mule Trails are successfully completed in the year 2017 in the highly affected communities of Gorkha and Rasuwa. There are altogether 41 critical stretches in Mule Trails that have been identified and rehabilitated after the Gorkha Earthquake. Among them, we have identified the most critical stretches in the Mule Tracks, one from Gorkha and one from each loops of Trails from Rasuwa Districts. The similar numerical and computational scheme can be applied for the remaining landslides identified in the Mule Tracks in Gorkha and Rasuwa Districts.

Figure 27 shows the stability analysis of Mule Trail at Kulkung Gang landslide, Gorkha (28-13-28.46N, 84-53-32.36E) that include landslide slope model, shear strain plots (kN/m^2) and strength Reduction actor, SRF (nos.) vs U_{max}(m). The shear strain plot gives a tentative idea of failure surface. Figure 28 shows the Pseudo-static seismic stability analysis (with variable horizontal seismic coefficient, EQx) of 0.1, 0.2 and 0.3. Similarly, the Figure 29, Figure 30 and Figure 31 respectively show the stability models, shear strain plots (kN/m^2) and strength reduction factor, SRF (Nos.) vs maximum horizontal displacement, Umax (m) of Mule Trail in varying sections of dry-stone wall (Type 1, 2 and 3) and soil-bioengineering (soil-root matrix of 1m).

The Figure 32 and Figure 33 respectively show the landslide model, shear strain plots (kN/m2) and SRF vs U_{max} (m) of the stability analysis of Mule Trail at 118m landslide, Rasuwa loop-1 (28-7-37.43N, 85-16-30.8E) of both barren and vegetated soil slopes (soil-bioengineering in the form of soil-root matrix continuum of 1m layer). Similarly, Fig. 34 and 35 respectively show the landslide model, shear strain plots (kN/m^2) and SRF vs Umax(m) of the stability analysis of Mule Trail at 102 m big landslide, Rasuwa loop-2 (28-1-10.58N, 85-15-7.86E) of both barren and vegetated soil slopes (soil-bioengineering in the form of soil-root matrix continuum of 1m layer).

The results demonstrate that variations in dry stone-wall cross-sections and soil slope conditions, including barren and vegetated surfaces, have a significant influence on the calculated factor of safety. The findings indicate that the slopes along the critical stretches of the Mule Track are stable under static loading conditions for both soil and rock slopes. Under pseudo-static seismic loading with a horizontal seismic coefficient (EQx) of 0.1, the slopes are marginally stable. However, they become unstable when subjected to higher seismic coefficients, indicating increased vulnerability to stronger earthquake shaking.

The critical Strength Reduction Factor (SRF) is identified from the SRF versus maximum displacement (U_{max}) plots by observing the point at which displacement increases abruptly with a small additional increase in SRF. This transition represents the onset of plastic deformation and the progressive loss of material strength. The inflection point indicates the transition from predominantly elastic to elastoplastic behavior. Therefore, an elastoplastic constitutive model is considered appropriate for representing the material behavior and evaluating slope stability in this study.

Table 6, The stability analysis of critical sections of Trails in Gorkha and Rasuwa districts

Landslide slope stability analysis at critical sections of Trails	Static soil/rock slope condition		Seismic soil/rock slope condition					
			0.1 g		0.2 g		0.3 g	
	Without Bio.	With Bio.	Without Bio.	With Bio.	Without Bio.	With Bio.	Without Bio.	With Bio.
Kulkung Gang landslide, Gorkha (28-13-28.46N, 84-53-32.36E)								
Type-1 Dry wall	0.94	0.97	0.78	0.84	0.70	0.76	0.66	0.68
Type-2 Dry wall	1.01	1.10	0.81	0.89	0.75	0.81	0.68	0.71
Type-3 Dry wall	1.06	1.16	0.84	0.91	0.76	0.87	0.70	0.76
118 m landslide, Rasuwa loop-1 (28-7-37.43N, 85-16-30.8E)								
Type-1 Dry wall	0.96	0.99	0.95	1.02	0.92	0.96	0.85	0.91
Type-2 Dry wall	1.02	1.10	0.98	1.08	0.97	1.00	0.88	0.94
Type-3 Dry wall	1.08	1.15	1.01	1.11	0.99	1.05	0.91	0.95
102 m big landslide, Rasuwa loop-2 (28-1-10.58N, 85-15-7.86E)								
Type-1 Dry wall	1.07	1.13	0.99	1.04	0.94	0.95	0.88	0.92
Type-2 Dry wall	1.11	1.17	1.02	1.07	0.97	0.99	0.91	0.96
Type-3 Dry wall	1.16	1.22	1.08	1.11	1.00	1.03	0.93	0.97

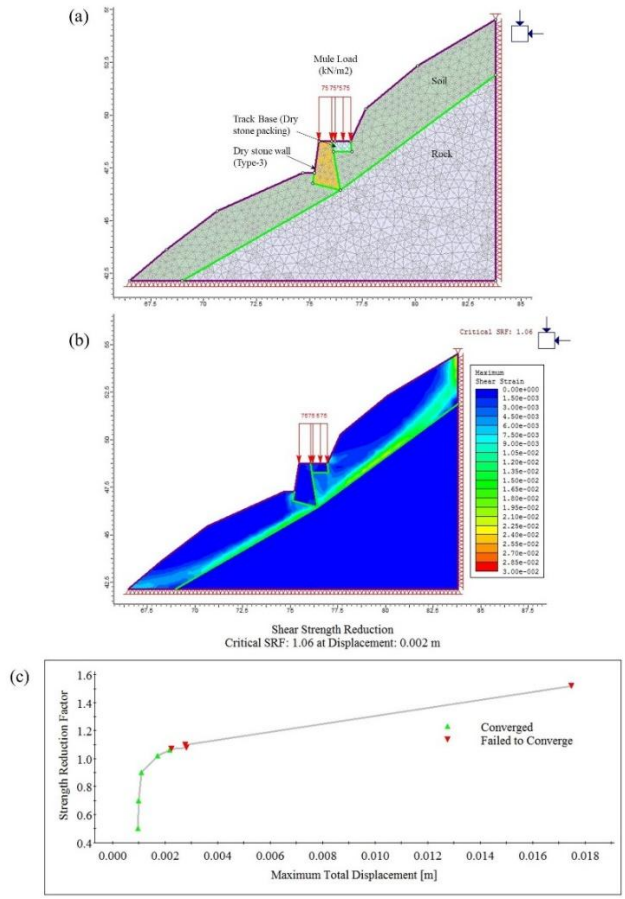


Figure 27, Stability analysis of Mule Trail at Kulkung Gang landslide, Gorkha (28-13-28.46N, 84-53-32.36E): (a) Landslide slope model, (b) Strain plots (kN/m^2) and (c) Strength Reduction Factor, SRF (nos.) vs U_{max} (m)

Table 6 presents the stability analysis of critical trail sections in Gorkha and Rasuwa Districts under both static and seismic conditions. The analysis considers different types of dry-stone walls with and without bioengineering measures. Results show that the inclusion of bioengineering consistently improves slope stability, increasing the factor of safety (FS) under static conditions and across seismic accelerations of 0.1g, 0.2g, and 0.3g. For instance, at the Kulkung Gang landslide in Gorkha, FS values rise from 0.94–1.06 without bioengineering to 0.97–1.16 with bioengineering. Similarly, critical landslides in Rasuwa (118 m in loop-1 and 102 m in loop-2) show notable FS improvements, demonstrating the effectiveness of combined structural and bioengineering interventions in enhancing trail resilience against static and earthquake-induced slope failures.

Figure 27 and Figure 28 illustrate the stability analysis of the Mule Trail at the Kulkung Gang landslide in Gorkha (28-13-28.46N, 84-53-32.36E). Figure 27 presents the landslide slope model, corresponding strain distribution (kN/m^2), and the variation of the Strength Reduction Factor (SRF) with maximum displacement (Umax), providing insights into slope behavior under static conditions. Figure 28 shows the pseudo-static seismic stability analysis for varying horizontal seismic coefficients (EQx = 0.1, 0.2, and 0.3), highlighting the trail's response under different earthquake loading scenarios and demonstrating the effectiveness of mitigation measures in enhancing slope stability.

These figures emphasize the critical role of site-specific analysis in designing resilient trail sections in landslide-prone areas. By combining slope modeling, strain distribution, and seismic response evaluation, the study identifies vulnerable zones and quantifies the benefits of structural and bioengineering interventions.

This approach ensures that the reconstructed trails can withstand both static and seismic stresses, improving safety, durability, and long-term usability for local communities.

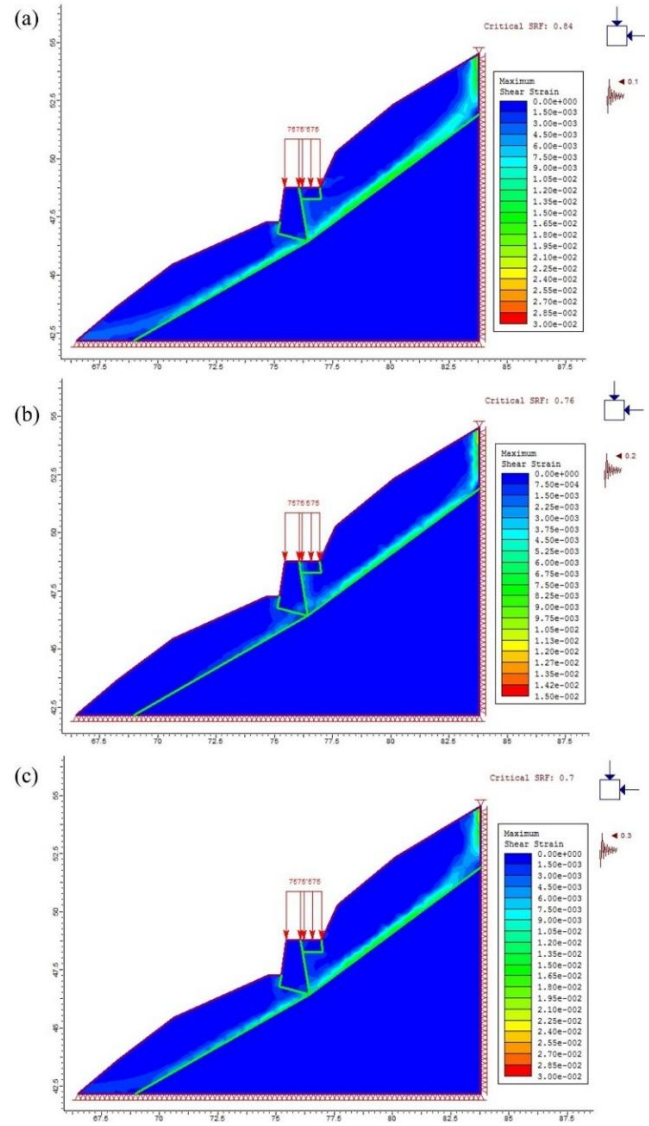


Figure 28, Pseudo-static seismic stability analysis (with variable horizontal seismic coefficient, EQx) of Mule Trail at Kulkung Gang landslide, Gorkha (28-13-28.46N, 84-53-32.36E): (a) EQx of 0.1, (b) EQx of 0.2 and (c) EQx of 0.3

Figure 29 and Figure 30 present the stability models and strain distribution of the Mule Trail at the Kulkung Gang landslide in Gorkha (28-13-28.46N, 84-53-32.36E) for varying dry stone wall designs combined with a 1 m soil-bioengineering (soil-root) matrix. Figure 29 shows the three types of dry wall sections (Type-1, Type-2, and Type-3) integrated with bioengineered soil, illustrating how structural variations influence overall slope stability. Figure 30 complements this by displaying the corresponding strain plots (kN/m^2) for each section, highlighting the areas of maximum stress and potential deformation under loading.

The analysis demonstrates that increasing the complexity and height of the dry-stone wall in combination with the soil-root matrix significantly improves the slope's factor of safety and reduces critical strain concentrations. This approach validates the effectiveness of hybrid structural and bioengineering interventions in mitigating landslide risks, ensuring safer and more resilient trails for the communities in Gorkha District.

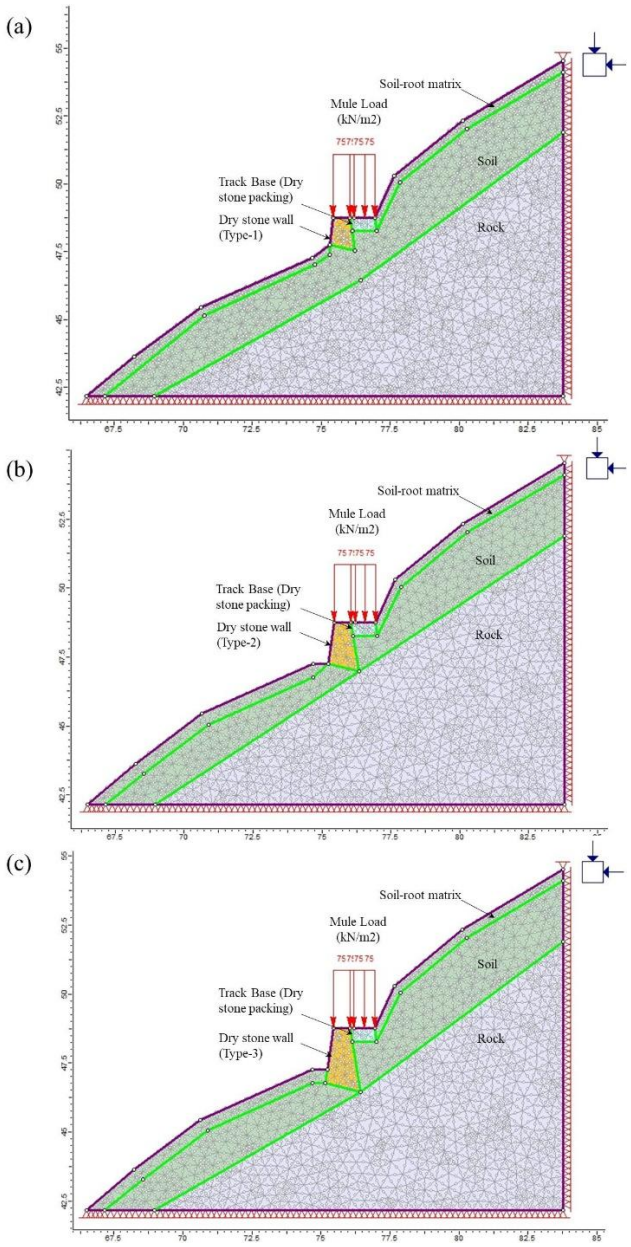


Figure 29, Stability models of Mule Trail at Kulkung Gang landslide, Gorkha (28-13-28.46N, 84-53-32.36E) in varying section of dry-stone wall and soil-bioengineering (soil-root matrix of 1m): (a) Type-1, (b) Type-2 and (c) Type-3

These figures also highlight the importance of optimizing trail design based on local slope conditions and available materials. By comparing the three wall types, it is evident that a tailored combination of dry-stone structures and bioengineered soil can effectively distribute stress, control deformation, and enhance slope resilience. Such targeted interventions not only prevent future landslide occurrences but also contribute to the long-term sustainability and safety of mountain trail networks in earthquake-prone regions.

This approach ensures that reconstructed trails remain stable under both static and seismic conditions. Moreover, it provides a practical model for resilient trail construction in other landslide-prone mountain regions.

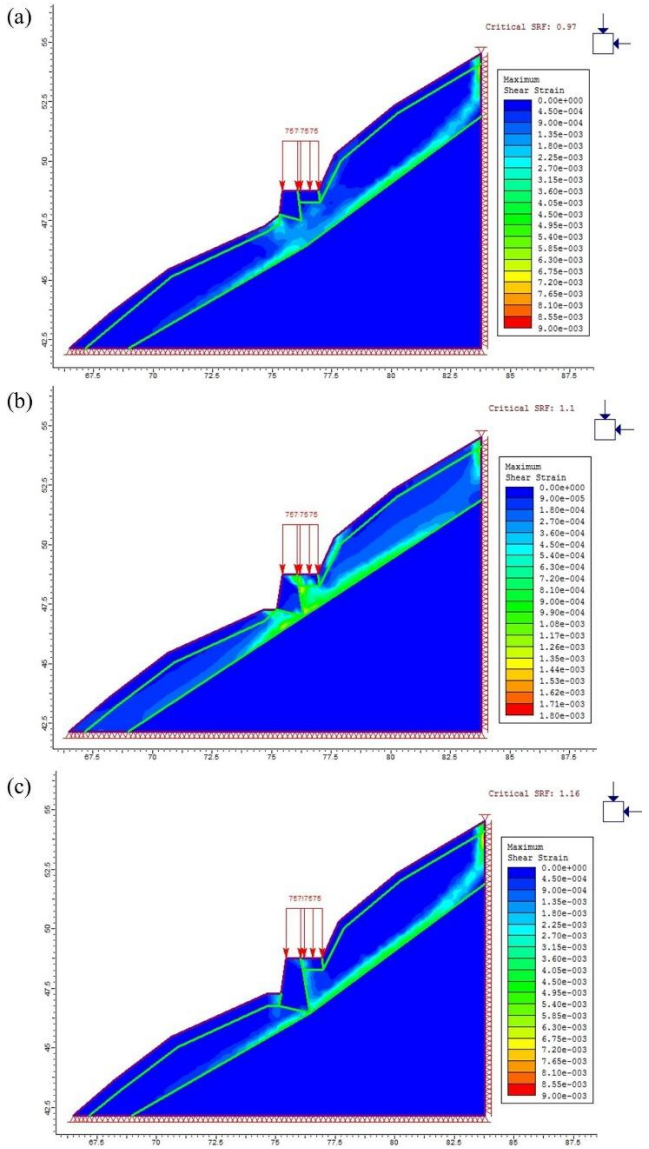


Figure 30, Strain plots (kN/m2) of stability analysis of Mule Trail at Kulkung Gang landslide, Gorkha (28-13-28.46N, 84-53-32.36E) in varying section of dry-stone wall and soil-bioengineering (soil-root matrix of 1 m): (a) Type-1, (b) Type-2 and (c) Type-3

Figure 31 and Figure 32 present detailed stability analyses of critical Mule Trail sections in Gorkha and Rasuwa Districts. Figure 31 shows the variation of the Strength Reduction Factor (SRF) versus maximum horizontal displacement (Umax) for the Kulkung Gang landslide in Gorkha (28-13-28.46N, 84-53-32.36E), comparing three types of dry-stone wall sections combined with a 1 m soil-bioengineering (soil-root) matrix. The plots highlight how different structural designs influence slope stability and deformation, providing insights into optimal mitigation measures.

Figure 32 focuses on the 118 m landslide in Rasuwa loop-1 (28-7-37.43N, 85-16-30.8E), presenting the landslide slope model, corresponding strain distribution (kN/m^2), and SRF versus U_{max} plots. These results illustrate the trail's response under static and pseudo-static conditions, emphasizing the effectiveness of combined structural and bioengineering interventions in enhancing slope resilience and ensuring safer, more stable trails in landslide-prone mountain regions.

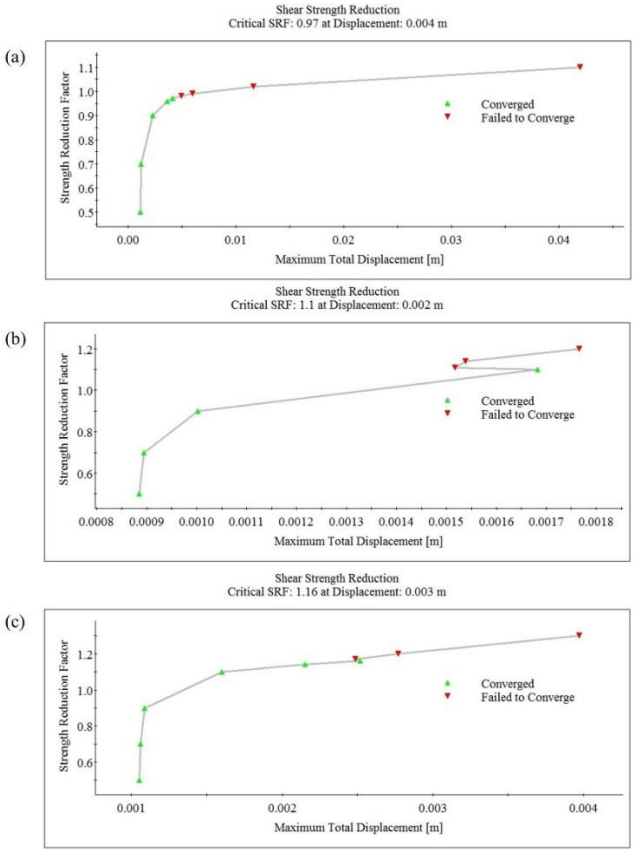


Figure 31, Strength reduction factor, SRF (Nos.) vs Maximum horizontal displacement plots, Umax(m) of stability analysis of Mule Trail at Kulkung Gang landslide, Gorkha (28-13-28.46N, 84-53-32.36E) in varying section of dry-stone wall and soil-bioengineering (soil-root matrix of 1m): (a) Type-1, (b) Type-2 and (c) Type-3

These figures underscore the importance of integrating site-specific structural solutions with bioengineering measures to improve slope stability along critical trail sections. By analyzing SRF and displacement for different wall types and soil-root matrices, the study identifies designs that effectively minimize deformation and distribute stress across the slope. This approach not only enhances trail safety but also prolongs the service life of the infrastructure. Additionally, it provides a replicable framework for resilient trail construction in other landslide-prone mountainous regions.

Moreover, the comparison between the Gorkha and Rasuwa sites highlights the variability in landslide behavior across different terrains. Such analyses enable engineers and planners to prioritize high-risk sections, implement targeted stabilization measures,

and develop resilient trail networks that can withstand future landslide and seismic events, ultimately supporting the mobility and safety of mountain communities. Overall, these findings serve as a valuable reference for future trail rehabilitation projects and disaster risk reduction strategies in the Himalayan region, ensuring safer and more sustainable mountain infrastructure. They also reinforce the importance of combining engineering expertise with local knowledge for effective mountain trail management.

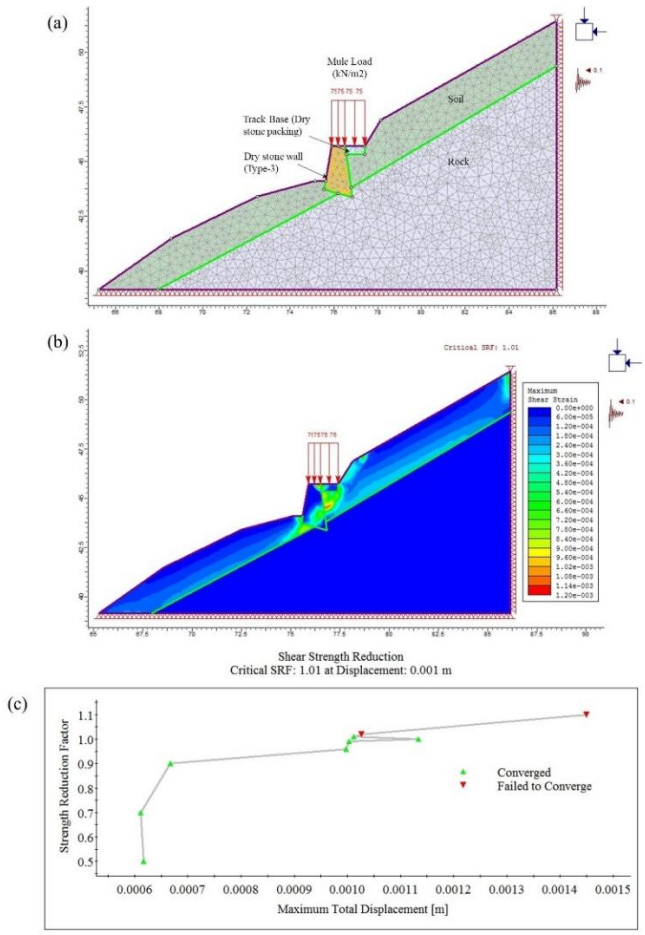


Figure 32, Stability analysis of Mule Trail at 118m landslide, Rasuwa loop-1 (28-7-37.43N, 85-16-30.8E): (a) Landslide slope model, (b) Strain plots (kN/m^2) and (c) Strength Reduction actor, SRF (nos.) vs U_{max}(m)

Figure 33, Figure 34 and Figure 35 present the stability analysis of critical Mule Trail sections in Rasuwa District, focusing on the 118 m landslide in loop-1 (28-7-37.43N, 85-16-30.8E) and the 102 m landslide in loop-2 (28-1-10.58N, 85-15-7.86E). Both analyses incorporate a 1 m soil-bioengineering (soil-root) matrix to evaluate slope behavior. Each figure includes the landslide slope model, corresponding strain distribution (kN/m^2), and the variation of the Strength Reduction Factor (SRF) with maximum horizontal displacement (U_{max}), providing a comprehensive assessment of slope stability under static and pseudo-static conditions.

The results demonstrate that integrating bioengineering measures with structural solutions effectively increases slope stability and reduces critical strain concentrations along the trail. By quantifying the slope response for these large landslides, the analysis supports targeted interventions that enhance safety, resilience, and long-term usability of the trails, ensuring reliable connectivity for communities in landslide-prone areas of Rasuwa District.

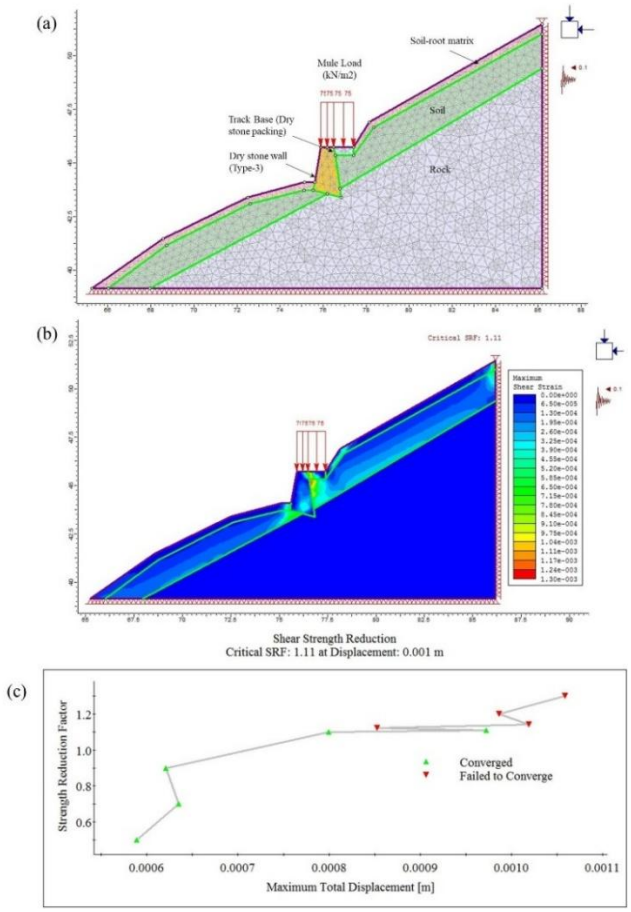


Figure 33, Stability analysis of Mule Trail at 118m landslide, Rasuwa loop-1 (28-7-37.43N, 85-16-30.8E) considering soil-bioengineering (soil-root matrix of 1m): (a) Landslide slope model, (b) Strain plots (kN/m^2) and (c) Strength Reduction actor, SRF (nos.) vs U_{max} (m)

These analyses highlight the significance of combining engineering and ecological approaches for trail stabilization in mountainous terrain. The soil-root matrix not only reinforces the slope but also promotes vegetation growth, which contributes to long-term slope cohesion and reduces erosion. Such integration of structural and bioengineering measures ensures that the trails remain stable under both normal and earthquake-induced loading conditions, minimizing the risk of future landslides.

Furthermore, comparing the 118 m and 102 m landslide sites underscores the need for site-specific designs, as slope geometry, soil conditions, and local topography influence stability outcomes. The findings provide valuable guidance for planning and

implementing resilient trail construction across similar landslide-prone regions, supporting both community mobility and sustainable mountain infrastructure development. These figures also emphasize the importance of continuous monitoring and maintenance of reconstructed trails. By understanding the behavior of slopes under varying conditions, engineers can prioritize critical sections for reinforcement, implement timely mitigation measures, and adapt designs based on observed performance. This proactive approach ensures that trails remain safe, functional, and resilient over time, even in the face of recurring landslides or seismic events.

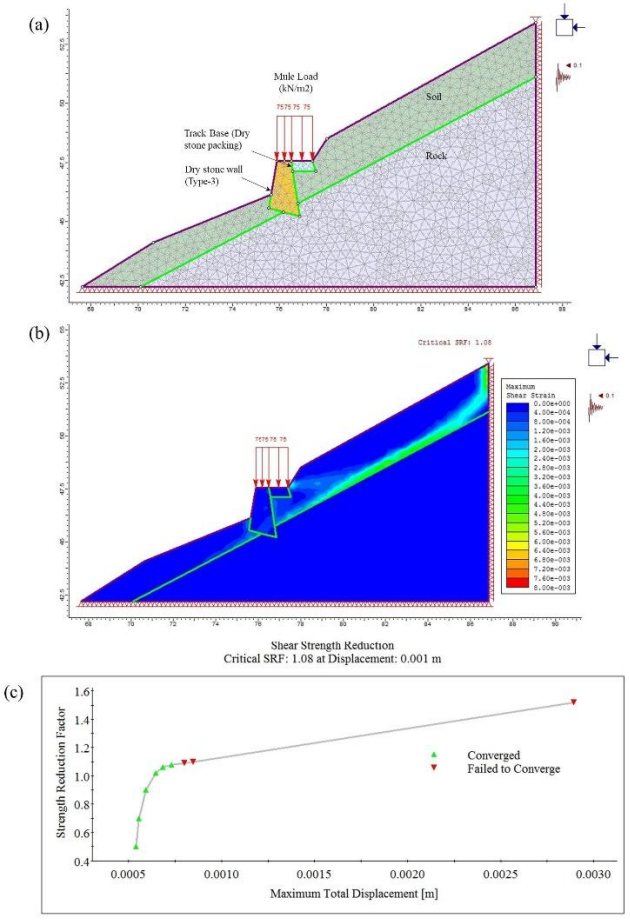


Figure 34, Stability analysis of Mule Trail at 102m big landslide, Rasuwa loop-2 (28-1-10.58N, 85-15-7.86E): (a) Landslide slope model, (b) Strain plots (kN/m^2) and (c) Strength Reduction actor, SRF (nos.) vs U_{max} (m).

Conclusion

The stability assessment of critical Mule Trail sections in Gorkha and Rasuwa demonstrates the importance of incorporating both geotechnical and seismic considerations into the planning and rehabilitation of mountain trails in earthquake-prone terrain. The two-dimensional FEM-based approach adopted in this study provides a useful framework for understanding the overall stability behavior of vulnerable trail sections and for evaluating the suitability of different stabilization strategies.

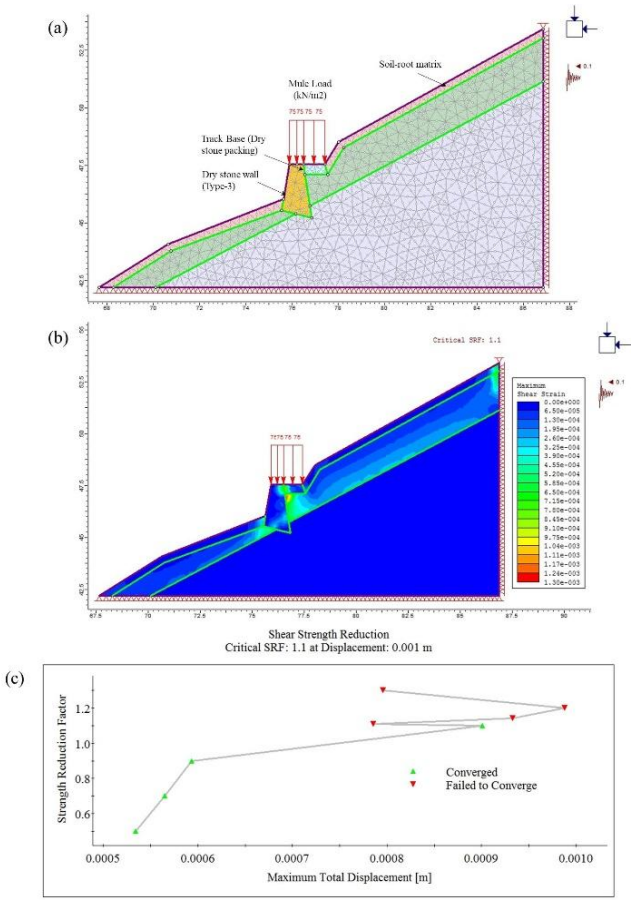


Figure 35, Stability analysis of Mule Trail at 102m big landslide, Rasuwa loop-2 (28-1-10.58N, 85-15-7.86E) considering soil-bioengineering (soil-root matrix of 1m): (a) Landslide slope model, (b) Strain plots (kN/m^2) and (c) Strength Reduction actor, SRF (nos.) vs U_{max} (m)

The study indicates that stability assessment of mountain trails cannot be based solely on static conditions. The additional effects imposed by earthquake-induced loading can substantially alter the stability state of an already vulnerable slope. Therefore, seismic considerations should be an integral part of the design, rehabilitation, and upgrading of mountain trails in the Himalayan region, particularly in areas affected by major earthquakes or located within active seismic zones.

The analysis further demonstrates the value of combining conventional structural stabilization with nature-based slope protection. Dry-stone walls provide immediate structural support, while soil-bioengineering offers an additional mechanism for improving surface reinforcement, reducing erosion, and promoting progressive ecological stabilization of the slope. The combination of these approaches is therefore more appropriate for mountain environments where long-term slope performance depends on both mechanical resistance and control of surface degradation.

An important implication of the study is that stabilization measures should not be implemented as a uniform solution across an entire trail network. Mountain slopes are highly heterogeneous, and their

response is governed by local geological, geomorphological, geometric, and environmental conditions. Consequently, the type and extent of stabilization should be determined through site-specific investigation and stability assessment. The numerical framework used in this study can assist in such prioritization by identifying sections requiring greater structural intervention and by supporting technically justified decisions regarding rehabilitation measures.

The study also highlights the relevance of locally appropriate and environmentally compatible construction practices. The use of dry stone and vegetation-based stabilization is particularly suitable for remote mountain trails, where construction materials, transportation, maintenance facilities, and skilled resources may be limited. Such approaches can reduce the need for heavily engineered solutions while maintaining compatibility with the surrounding natural environment. Their successful application can therefore contribute not only to slope stability but also to the sustainability and social functionality of rural trail infrastructure.

The rehabilitation of Mule Trails should also be considered as a continuing process rather than a one-time construction activity. Even a stable slope at the time of construction can experience progressive deterioration due to intense rainfall, surface erosion, drainage problems, weathering, vegetation changes, and subsequent seismic activity. Regular inspection and maintenance of drainage systems, dry-stone structures, and vegetated slopes are therefore essential for maintaining the performance of the rehabilitated trails. Particular attention should be given to sections identified as critically vulnerable through numerical analysis and field observations.

The methodology developed in this study can be extended beyond the three representative sections examined here. The identification of additional critical stretches along the Mule Trail network provides an opportunity to apply a similar analytical framework for systematic risk assessment and prioritization. Such an approach could support the development of a broader trail-slope management system in which vulnerable sections are assessed according to their geological setting, slope condition, seismic exposure, and required stabilization measures.

Finally, the findings emphasize that resilient mountain infrastructure requires an integration of engineering analysis, appropriate construction practices, ecological measures, and continued field-based management. The experience from the post-earthquake rehabilitation of Mule Trails in Gorkha and Rasuwa provides a useful basis for improving future trail development and disaster-risk reduction initiatives in Nepal. The approach presented in this study can contribute to the development of safer, more durable, and environmentally sustainable mountain transportation networks, particularly in regions where landslides and earthquakes pose recurrent threats to community connectivity.

Acknowledgements

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Article note

This article is a full-length paper developed from **Extended Abstract #209**, entitled "**Post-Earthquake Stability and Rehabilitation of Mountain Trails ('Unnat Goreto') in Gorkha and Rasuwa Districts, Nepal**" which was presented at the 15th Asian Regional Conference of the International Association for Engineering Geology and the Environment (ARC-15 of **IAEG**), held in Kathmandu, Nepal, from 27 to 29 November 2025.

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