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Engineering Geological Study and Slope Stability Analysis along the Kanti-Rajpath from Chun Danda to the Simat Khola, Central Nepal

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Abstract: Stability analysis of the cut slope of a road section is necessary to prevent damage to the road and the surrounding environment. The study encompasses engineering geological assessment, the cut and fill slope failure analysis of the road section of the Kanti-Rajpath from Chun Danda to the Simat Khola, Makwanpur. Four different cut and downslope critical slopes were selected to represent the overall road section for stability modeling. Four slopes were chosen based on high cut-angle, lithology and visible slope instability to represent the range of conditions along the alignment. The maximum 1-day monsoon rainfall data was used for seepage modeling using the FEM-based software SEEP/W and stability analysis to calculate the Factor of Safety (FOS) using SLOPE/W software of GeoStudio package. The results indicate that the slope appears to be marginally stable to unstable under the given rainfall condition. Our results indicate FOS values of 0.78–1.9, underscoring the need for drainage and slope-angle control. Approximately 7 km of the 20 km road section, especially at the gully portions which are highly vulnerable, needs to be managed. Since the highway serves a direct connection between the capital and the Terai, slope management of this road section is critical for the nation's economic growth.

Keywords: ***FEM-based cut slope stability, Kanti Rajpath, Engineering geological map.***

Introduction

Slope failures are widely occurring throughout the world, particularly along the road cut slopes constructed in hilly/mountainous regions often leading to loss of life and property (Sharma et al., 2017; Shrestha, 2021; Singh et al., 2008). Whenever slopes are modified from their natural state for road construction and widening activities, slope instability may occur due to improper modifications (Sarkar et al., 2016). Slope failure can result in the loss of life and property; hence it's important to double-check the requisite slope's stability. Slope geometry, slope material type, strength, hydrological condition, structural discontinuities, lithological and weathering conditions etc. are the different factors which initiate the slope failure. Slope stability analysis simply means to calculate the factor of safety of any slip surface associated with a failing slope and find out the critical failure surface. If the factor of safety (FOS) is greater than 1, it means slope is stable and less than 1 means already failed.

After 1970, stability analysis started to be performed using various software such as GeoStudio, PLAXIS, Slide etc. The most widely used analytical method is the Limit Equilibrium Method-LEM (Anbazhagan, 2017; Jinyu et al., 2010; Kharel and Acharya, 2017) but nowadays the numerical methods (Finite Element Methods-FEM, Finite Difference Method-FDM) have become popular in case of slope stability problems for the prediction of unknown states by solving appropriate governing equations which can predict and control the real slope system. Numerical modeling will simplify the complexity of nature with the sparse data and proper understanding of the analysis.

Recent studies in Nepal have increasingly incorporated more detailed field data, geophysical investigations, and numerical modelling. For example, Shrestha et al. (2023) used 2D-ERT and lab tests to model cut-slopes in the Lesser Himalaya and showed that slope angle reductions or soil-nailing can improve factor of safety substantially. Bhandari et al. (2023) evaluated a 60 m high rock cut slope, showing how discontinuities, groundwater, and seismic loads affect stability. Most commonly the performance of traditional LEM and recent numerical method FEM has been compared and combined to examine the stability of road cut slopes, natural slopes of soft material, post-quake slopes, embankments etc. (Ansari et al., 2020; Burman et al., 2015; Bushira et al., 2018; Dahal et al., 2009; Hammouri et al., 2008; Huo and Zhai, 2012; Kumala, 2015; Lim et al., 2017; Wang et al., 2013). In Nepal, rainfall is the major triggering factor for the roadside slope failures (Dahal et al., 2006). The application of roadside cut slope stability assessment can help minimize failures caused by slope modifications (Lee et al., 2009). However, there remains a gap in applying these more advanced methods to many of Nepal's alternative or less-studied routes (such as Kanti-Rajpath), especially for engineering geological mapping combined with FEM-based modelling across full road sections.

Kanti Rajpath is an alternative route that connects Capital city Kathmandu to Terai region of Nepal. In 1959, the late King Mahendra came to Kathmandu from Hetauda on his own taxi, but now it is challenging task for taxis also to go smoothly through this road section due to the problem of landslides, slope instability, road cracks and water runoff (Figure 1). Makwanpur Gadhi is a potential place for tourism in Makwanpur district, and it is very difficult nowadays to reach that place from the capital.

The research site is a road section of the Kanti-Rajpath from Chun Danda Road junction to the Simat Khola bridge, Thingan, Makwanpur District of Central Nepal (Figure 2). The research aims to prepare a detailed engineering geological map along the road section and highlight the current slope stability situation of the Kanti-Rajpath and identify required mitigating measures for stable slopes. This paper includes the FEM based stability analysis and engineering geological mapping of the road section of Kanti Rajpath to present the stability condition of that section.

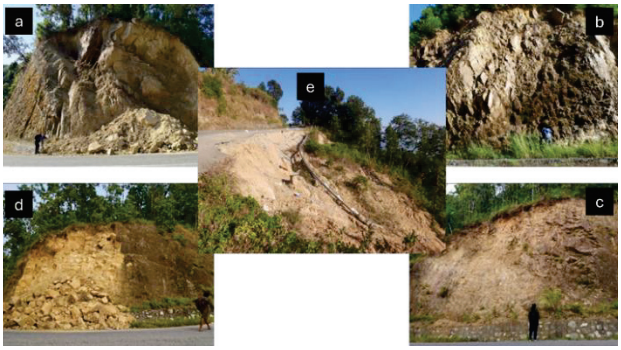

Figure 1, Representative slope conditions along the selected road section; a) Rockfall at Jitpur Bhanjyan, b) Joint sets at Taplakhar, c) Slope condition at Shikhar Kateri, d) Rock fall at Shikhar Kateri and e) Down slope failure at Bar Bhanjyan.

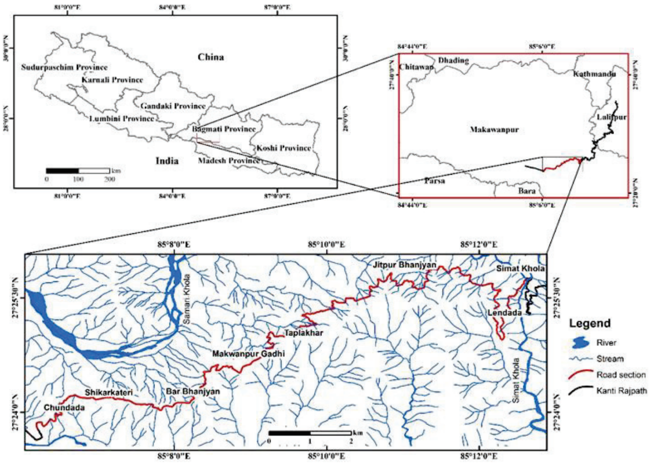

Figure 2, Location map of the study area.

Geological setting

Geologically, the stretch of road section of the Kanti-Rajpath belongs to the Siwalik, comprising sedimentary rocks such as mudstone, sandstone to pebbly sandstone and conglomerate. The Siwalik is the youngest southernmost Himalaya zone which is bounded by the Main Boundary Thrust in the north and the Main Frontal Thrust in the south. It is overlain on the plain of Indo Gangetic Basin in the south. Siwalik is divided into Lower Siwalik, Middle Siwalik, and Upper Siwalik subgroup (Auden, 1935). The stratigraphy of the Siwalik Group at different area of Nepal has also been established (Auden, 1935; Corvinus and Nanda, 1994; Glennie and Ziegler, 1964; Rai and Yoshida, 2020; Tokuoka et al., 1990; Ulak and Nakayama, 1998; Ulak, 2009; Yoshida and Arita, 1982). Ulak and Nakayama (1998) studied the Siwalik Group of Central Nepal and divided into subgroup: the Rapti Formation, the Amlekhgunj Formation, the Churia Khola Formation, and the Churia Mai Formation.

Geomorphology

The road section of the Kanti-Rajpath from Chun Danda to the Simat Khola lies within rugged Siwalik terrain, characterized by moderate to high relief and steeply dissected slopes. Similar to other Siwalik areas of central Nepal, slope angles typically exceed 30° to more than 45° in cut slopes (Subedi and Tamrakar, 2020). Numerous active gullies incise the road corridor and deliver large sediments during monsoon storms, well documented in nearby Siwalik catchments (Ghimire et al., 2006). Small streams and tributaries drain the slopes causing stream-bank erosion and debris flow during intense rainfall (Ghimire et al., 2013). The alternating beds of sandstone, mudstone and conglomerate typical of the Siwalik further influence erosion and slope instability. This combination of steep slopes, gullies and weak lithology makes the road corridor highly susceptible to failures.

Methods

Field mapping

Engineering geological mapping of the study area was carried out along the cut slopes and downslope sections of the Kanti-Rajpath Highway. All the information about the geological, geomorphological, hydrological, and hydrogeological aspects were incorporated into a 1:10,000 scale engineering geological map. The mapping included lithology, soil type, soil depth, Unified Soil Classification system (USCS soil classification), streams, weathering grade, seepages and landslides. Geological Strength Index (GSI) were determined for the assessment of rock mass quality. GSI value was evaluated using surface condition and structure ratings based on visual field estimation and applied here using the chart established by

(Sonmez and Ulusay, 1999) for a more quantitative numerical basis of strength of Siwalik rocks.

Kinematic analysis

Kinematic analysis of potential rock slope failures was performed on joint data collected from different slopes (T8, T11, T39, T40, T56, T58, T62, T73, T77, T89) along the Kanti-Rajpath Highway (Figure 3). At each site the attitudes (dip amount and dip direction) of all major discontinuity sets were measured using a Brunton compass.

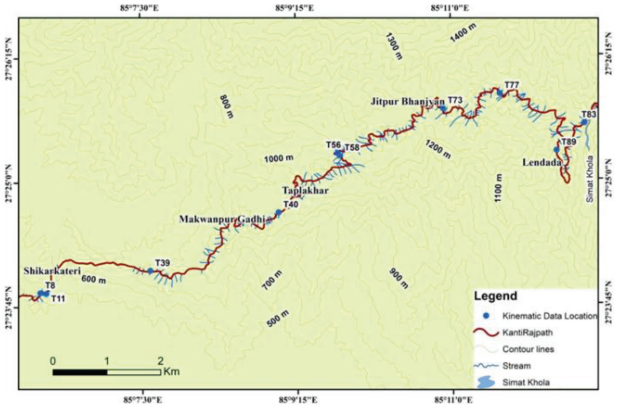

Figure 3, Kinematic data collected location along the study road section.

The discontinuity data were plotted on lower-hemisphere stereographic projections using Dips v6.0 software. In these projections, great circles represent discontinuity planes, and their intersections indicate potential wedge lines. Potential planar, wedge and toppling failures were then evaluated using the failure criteria given by Hoek and Bray (1981).

Slope selection and FEM-based stability modelling

To represent the range of conditions along the road (Figure 4), four representative cut and downslope soil slopes (SS1–SS4: Figure 5, Figure 6, Figure 7, Figure 8) were selected based on slope angle, lithology and visible slope instability and spatial coverage.

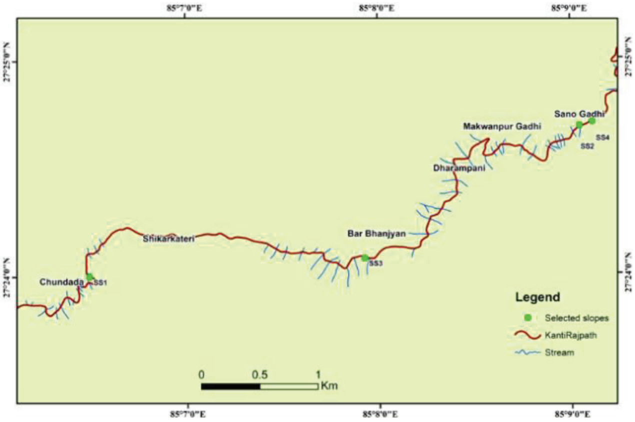

Figure 4, Map showing the locations of selected slopes for stability analysis.

Subsoil samples were collected from landslide (colluvial) material using hand auger, sampler and geological hammer. All soil samples were sealed in airtight plastic bags and labeled with sample number and GPS coordinates. Remolded samples were prepared from disturbed material; no intact cores were recovered. The samples were tested in the laboratory following ASTM standards: grain size analysis by sieve and hydrometer (ASTM D422), Atterberg limits (ASTM D4318), and direct shear tests (ASTM D3080). Direct shear tests were conducted on remolded soil specimens at normal loads of 19, 38 and 76 kPa with a displacement rate of 0.5-1.0 mm/min.

Figure 5, Slope SS1.

Figure 6, Slope SS2.

Figure 7, Slope SS3.

Figure 8, Slope SS4.

Slope stability analysis was performed using FEM based stability analysis in GeoStudio 2021. GeoStudio is a coupled hydrological slope stability model in which both SEEP/W and SLOPE/W are collectively used for simulation. SEEP/W is a FEM based program in GeoStudio which simulates the distribution of pore water pressure (PWP) in the slopes. To predict the porewater pressure developed due to the rainfall infiltration, hydrological models have been used widely. SEEP/W uses a numerical discretization technique to solve Darcy's equations for unsaturated and saturated flow conditions and runs the following water-flow governing equation in each time step to compute two-dimensional seepage (Eq. 1).

$$\frac{dy}{dx}\left(K_x\frac{dH}{dx}\right)+\frac{d}{dy}\left(K_y\frac{dH}{dy}\right)+q=m_w^2\rho_w\frac{dH}{dt} \tag{1}$$

Where,

K_x, K_y is the coefficient of permeability in x-direction and y-direction,

H is the hydraulic head or total head,

q is the applied flux at the boundary,

m_w is the slope of the soil-water characteristic curve, and

ρ_w is the unit weight of water.

For the seepage analysis, it is needed to provide permeability function, the characteristic curve of soil-water, boundary flux and water table to define the slope problem.

The geometry of slope was obtained by ranging rod for profile and compass bearing survey for boundary. These obtained geometries were sketched on the geo-slope blank document to proceed with the modeling. The interface of soil and rock surface was drawn as per the slip surface observed in the field. The thickness of the colluvium soil layers was selected as per the field observation. The measured hill slope and cut slope angle were used for modeling. Contact between soil and rock was geometrically planar, having soil layers parallel to the ground surface. The hydraulic conductivity functions and volumetric water content functions were defined as per the lab and field test data of grain size distributions of colluvial soil. The boundary conditions used are the null flux to the upslope and interface of soil and rock, null flux with potential seepage face on the downslope, and rainfall with potential seepage face along the slope face. Water tables are considered at the boundary of soil and rock. After defining all these, the modeling was run.

The Morgenstern-Price (1965) method was used to calculate the FOS. It satisfies both the force and moment equilibrium, so can be applied to any kind of slip. The result of transient seepage analysis can be used as the parent analysis for the stability analysis through SLOPE/W with the definition of material (Mohr-Coulomb model) and entry and exit of the slip surface because SLOPE/W lacks the dynamic modeling of pore water pressure.

Results

The study road section from Chun Danda to Simat Khola lies in the Siwalik Zone of Central Nepal and comprised the Lower Siwalik Formation, Middle Siwalik Formation (Lower Middle Siwalik and Upper Middle Siwalik member) of Siwalik in Central Nepal. The Lower Siwalik comprises variegated mudstone, shales interbedded with thinly bedded fine grained sandstone. The lower Middle Siwalik (MS1) consists of moderately thick beds of medium-grained sandstone interbedded with "pepper and salt" textured medium-grained sandstone. The upper Middle Siwalik (MS2) consists of interbeds of medium-grained sandstone, calcareous mudstone with a moderately thick bed of pebbly sandstone with moderate weathering (Table 1). Weathering and lithological variations strongly influence the engineering behavior of the slopes along the road.

Table 1, Siwalik lithostratigraphy of the study region.

Formation/Member	*Lithology*	*Grain size*
Upper Middle Siwalik (MS2)	Medium-grained sandstone, calcareous mudstone with pebbly sandstone	Sand-gravel
Lower Middle Siwalik (MS1)	Moderately thick medium-grained sandstone interbedded with "pepper and salt" sandstone	Sand
Lower Siwalik	Variegated mudstone & shale with thin fine-grained sandstone	Clay-silt

Engineering geology of the road section

The engineering geological mapping of the 20 km road section includes lithology, soil type, soil classification, weathering pattern, the presence of gullies and seepages, and slope failures, along with mass strength indices. The 1:10,000 scale engineering geological map (Figure 9) shows lithology, soil classification, weathering pattern, gullies, seepages, slope failures with corresponding GSI values.

The mapped terrain is rugged, with moderate to high relief, steep slopes (20°–70°), and deeply incised gullies. Residual soil depth ranges from <1 m in fresh Lower Siwalik to 1–1.5 m in highly weathered MS1 sandstone. Small landslides (<30 m) occur in the lower section, while larger failures are observed near Bar Bhanjyan, Gadhi, Jitpur Bhanjyan, and Gairigau. Wide road cuts, steep slopes, and weak lithology are the main engineering challenges for this road section.

Kinematic analysis

Lower-hemisphere stereographic projections show three main joint sets within the Siwalik rocks along the study section (Table 2). The plotted data of slopes revealed wedge failure is the most common potential mode at most sites (up to 56.7 % at T77), followed by plane failure (up to 30 %) and toppling (generally <25 %).

Table 2, Joint sets and potential failure modes.

Site	*J1 (°/°)*	*J2 (°/°)*	*J3 (°/°)*	*Plane (%)*	*Wedge (%)*	*Toppling (%)*
T8	345/55	105/68	125/60	28.0	51.2	24.6
T11	350/60	116/30	240/73	3.3	26.3	5.8
T39	050/20	195/65	290/88	18.5	31.7	20.3
T40	070/35	190/65	275/75	0.0	9.3	4.6
T56	350/35	190/75	268/75	30.0	37.9	3.5
T58	340/25	216/83	155/78	16.7	37.1	2.3
T62	345/25	265/80	170/80	5.4	14.3	5.1
T73	010/55	100/72	195/85	14	21.3	4.5
T77	010/50	105/70	270/66	24.0	56.7	3.7
T89	004/36	090/78	130/71	0.0	1.9	8.6

Slope condition and stability modelling

Slope material of SS1 (cut slope) and SS3 (down slope) consist of clay to very fine sand, representing moderately weathered Lower and Lower Middle Siwalik slopes. SS2 (cut slope) and SS4 (down slope) comprise sandy sediments, representing highly weathered Lower Middle Siwalik slopes with "pepper and salt" texture (Table 3).

The maximum 1-day annual rainfall from Makwanpur Gadhi station (2010–2020) was used for modeling. The rainfall was applied in 240-time steps of 6-minute intensity to simulate transient seepage using SEEP/W (GeoStudio). The results were used as input for slope stability analysis in SLOPE/W, where the Mohr-Coulomb failure model was applied, and entry and exit points of the slip surface were defined manually due to SLOPE/W's limitations in modeling dynamic pore pressures. The slope profiles and stability results are shown in Figure 10, Figure 11, Figure 12 and Figure 13.

The parameters required for stability analysis, including unit weight, cohesion, internal friction angle, and saturated water content of each soil layer, are presented in Table 4.

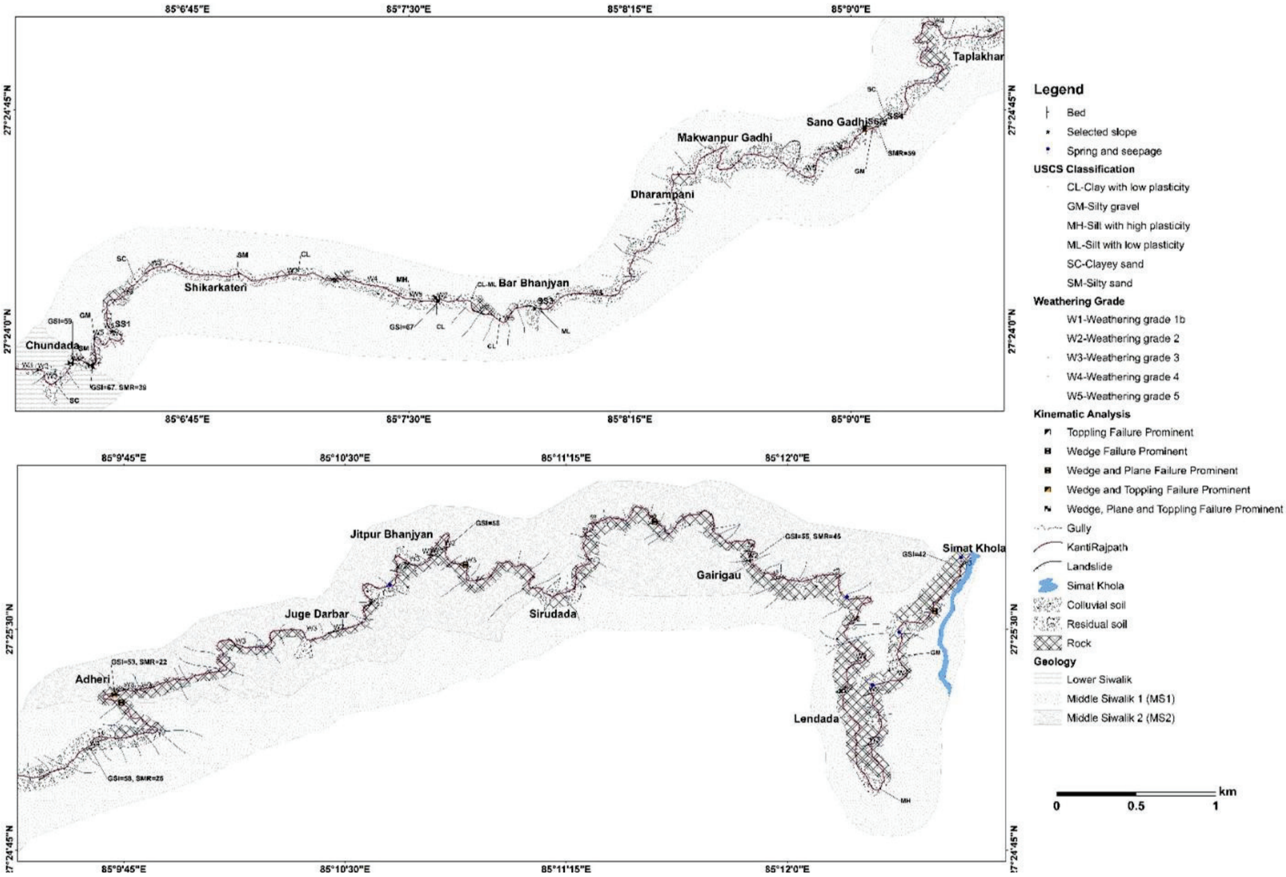

Figure 9, Engineering geological map of the study area.

Table 3, Summary of key parameters of selected slopes.

Slope ID	**Location**	**Slope Type**	**Height (m)**	**Soil Type**
SS1	Chundanda	Cut slope	10–15	Clay to very fine sand
SS2	Gadhi Bazaar	Cut slope	25	Sandy sediments
SS3	Bar Bhanjyan	Downslope	32	Clay to very fine sand
SS4	Gadhi Bazaar	Downslope	70	Sandy sediments

Table 4, Data used for slope stability analysis.

Layers	**Cohesion (kN/m^2)**	**Frictional angle (°)**	**Unit weight (kN/m^3)**	**Liquid limit**	**Saturated Water Content**
SS-1a	32.55	17	19.306	32.47	0.38
SS-1b	4.58	38	15.386	44.41	0.43
SS-1c	5.96	36	17.542	34.28	0.43
SS-1d	2.12	33	16.464	17.42	0.46
SS-2	5.33	29	16.85	17.24	0.43
SS-3	3.69	39	15.19	33.41	0.46
SS-4	11.7	25	16.95	18.13	0.43

The maximum 1-day annual monsoon rainfall of Makwanpur Gadhi station (2010-2020) was modeled in the simulation. The monsoon rainfall event of 1 day maximum was divided into 240 steps of 6-minute intensity and seepage into the soil was simulated using SEEP/W, GeoStudio. FEM-based transient seepage and stability modeling of four representative slopes under 1-day maximum rainfall showed FOS ranging from 0.78 to 1.946. Small cut slopes like SS1 (Chun Danda) were stable (FOS = 1.8), while steep cut slopes and tall downslope failures like SS2 (Gadhi Bazaar, FOS = 0.814) and SS4 (Gadhi Bazaar, FOS = 0.78) were unstable. Maximum pore pressures ranged from 2.03 to 5.39 kPa. The slope profiles with their stability analysis results are shown in Figure 10, Figure 11, Figure 12 and Figure 13.

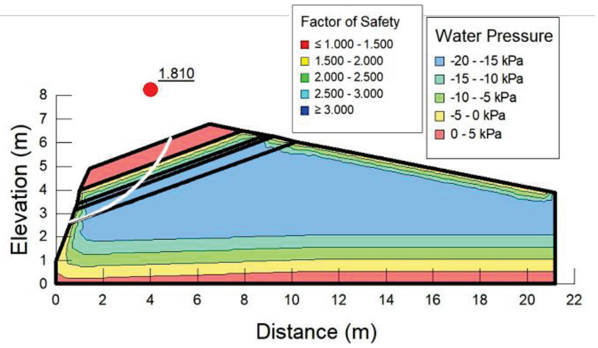

Figure 10, Stability analysis of SS1.

Discussion

Slope failures in the Siwalik region are widely reported due to the combination of weak lithology, steep slopes, and intense monsoonal rainfall. Road-cut slopes are particularly vulnerable as excavation alters the natural slope geometry, reduces stability and increases susceptibility to rainfall-induced landslides.

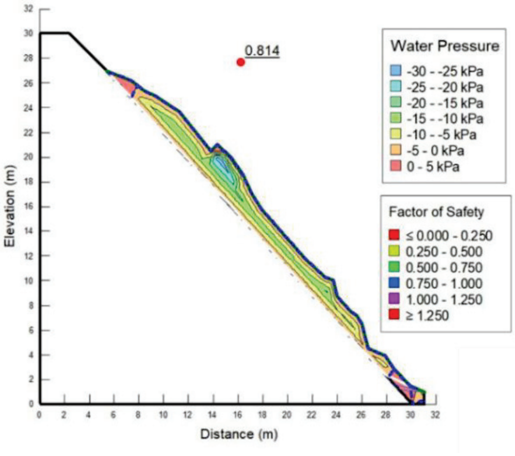

Figure 11, Stability analysis of SS2.

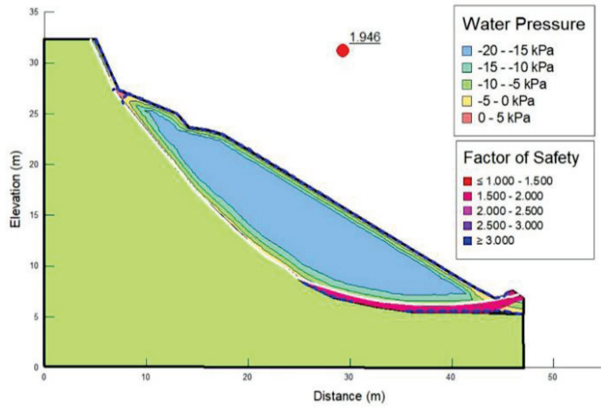

Figure 12, Stability analysis of SS3.

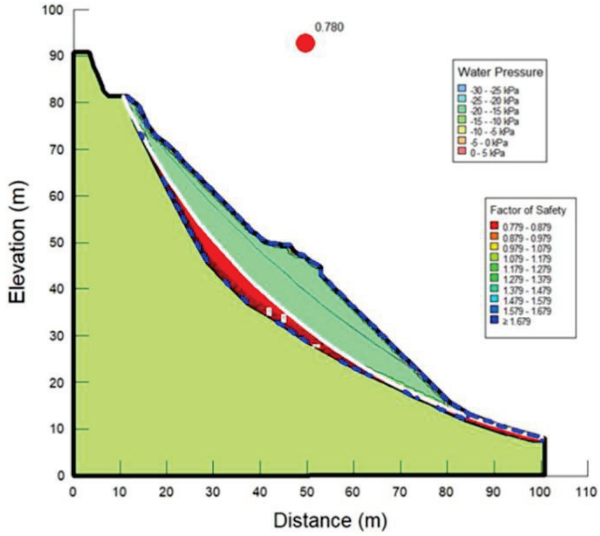

Figure 13, Stability analysis of SS4.

The computed FOS values (0.78-1.95) along the Kanti-Rajpath align closely with findings from other Himalayan studies. Ansari et al. (2020) reported FOS 0.7-1.8 for Lesser Himalaya road cuts, Sharma et al. (2017) observed similar instabilities in unconsolidated hill slopes in India, and Dahal et al. (2006) identified rainfall infiltration as the dominant trigger for slope failures. This comparison underscores that Siwalik road-cut slopes are highly sensitive to rainfall, lithology and slope geometry.

This study is novel in combining detailed engineering geological mapping with FEM-based transient seepage modeling. This integrated approach allows identification of high-risk slopes, quantification of rainfall-induced pore pressures, and understanding of failure mechanisms, particularly wedge-dominated failures. The results provide practical guidance for slope stabilization, including slope-angle optimization, drainage improvement, and reinforcement of weak lithologies. This approach is directly applicable for landslide mitigation and road maintenance in Siwalik terrains.

Conclusion

The following conclusions are drawn exclusively from this study.

- The lower and Middle Siwalik slopes, particularly the lower Middle Siwalik contain thick weathered sandy soils, contributing to slope instability.
- FEM-based slope stability analysis under 1-day maximum rainfall shows FPS value ranging from 0.78 to 1.946, indicating slopes are unstable to marginally stable.
- Approximately 7 km of the 20 km road section exhibit stability issues, including rockfall, circular failures, and planar sliding, especially near Chun Danda, Bar Bhanjyan, Gadhi, Jitpur Bhanjyan and Gairigau.
- Avoid vertical or very steep cut slopes to reduce risk of failure
- Implement drainage, optimize slope angles and use retaining structures where needed.
- Monitor the vulnerable slopes, especially in gully areas.
- Integrate engineering geological mapping and slope stability assessment into future road planning in the Siwalik terrains.

Author contributions

Anjla wrote the manuscript, prepared the figures, and revised the article. She is the sole author.

Data availability

No datasets were generated or analyzed during the current study.

Declarations

The author declare that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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