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Engineering Geological Study of Road Tunnel Along Siddhartha Highway Between Butwal and Dobhan Siwaliks Group, West-Central Nepal

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Abstract: The Siddhartha Highway is a critical economic artery in Nepal, providing a vital trade link with China and India. However, this roadway has been beset by the frequent occurrence of rock falls and dry landslides, which can cause severe damage and disruption. The main causes of these issues are differential weathering patterns of the rocks, activation of the Main Frontal Thrust, and a young mountain chain with fragile geology. Because of road instability, the road tunnel has been proposed to prevent damage. The proposed tunnel road passes between the chainage of 29+000 and 30+370 in the rocks of the Lower and Middle Siwaliks. The Lower Siwaliks are composed of thick to thin-bedded shale, mudstone, and calcareous sandstone, whereas the Middle Siwaliks are represented by presence of friable sandstone, shale, and mudstone. The rock mass of this section varies from poor rock to extremely poor rock with Rock Mass Rating (RMR) values ranging from 29 to 45 and *Q*-values ranging from 0.19 to 1.11. The support system for each class is derived according to RMR and Q-value. The kinematic analysis reveals the potential of wedge failure at the southern portal of the road tunnel, whereas the northern portal has shown a low potential for failure.

Keywords: engineering geological mapping, rock mass classification, road tunnel, support system

1. Introduction

Nepal's rugged topography presents significant challenges for roadway infrastructure, particularly in hilly and mountainous regions, where rock fall and landslides are major issues in wet and dry seasons. Each year, Nepal experiences hundreds of devastating landslides and roadside slope collapses that cause tremendous loss of life and property, and the yearly rate of human deaths in landslides and related disasters still stands at over 300 deaths per year in Nepal [1, 2]. To mitigate these challenges, the most effective solution is an efficient road network, supported by the construction of tunnels. According to [3], establishing an effective road network will facilitate connectivity between various regions of the country and commercial centers, thus playing a significant role in promoting economic and social progress. The study focuses on an engineering geological study of the proposed road tunnel in Siddhababa along the Siddhartha Highway area.

North of Butwal city is situated in the Siwaliks and separated by the active thrust of the Himalayan Frontal Thrust. The Siwaliks are comprised of mudstone and sandstone. Because of fragile geology, the occurrence of differential weathering in rocks is the most critical factor for assessing the stability of road alignment. This section of the Siddhartha Highway between chainages of 29+000 and 29+370 is influenced by active rock fall zone. Generally, plane failures are seen in bedrocks compared to the wedge failure resulting from a south-west facing joint set. Additionally, the Siddhababa section in the Siddhartha Highway is highly susceptible to block failure, gully erosion, and slope scarring, which is hazardous and requires structural countermeasures [4].

Bokati et al. [5] simulated rock fall along the highway between the Chidiya Khola and Dobhan (28+200–32+600) in six different profiles using GeoRock 2D software, which identified this as a critical site for rock fall hazards along the highway.

The study area lies between the Chidiya Khola and Dobhan, 29+000 to 30+370 Palpa district, west-central Nepal. This section falls in Siwalik Range. The study area lies about 1 km north from Butwal and 269 km from west of Kathmandu (Figure 1). Geologically, the area lies in Siwalik Range covering the rocks of the Lower and Middle Siwaliks and extends from 27°42'43.2''N to 27°44'31''N latitudes and 83°27'7'' to 83°29'27'' E longitudes.

Therefore, the objectives of this study are to determine the rock mass characteristics of the study area that will host the road tunnel section and pre-existing road section of the Siddhartha Highway between the chainage 29+000 to 30+370, establish a reliable support system, and assess the stabilities of rock slopes.

2. Materials and Methodology

Route map as well as engineering geological map along the road section with detailed columnar section of the bedrocks exposed along the road has been prepared in scale of 1:1000 scale. Discontinuities are measured to calculate Rock Mass Rating (RMR) and Q-value for

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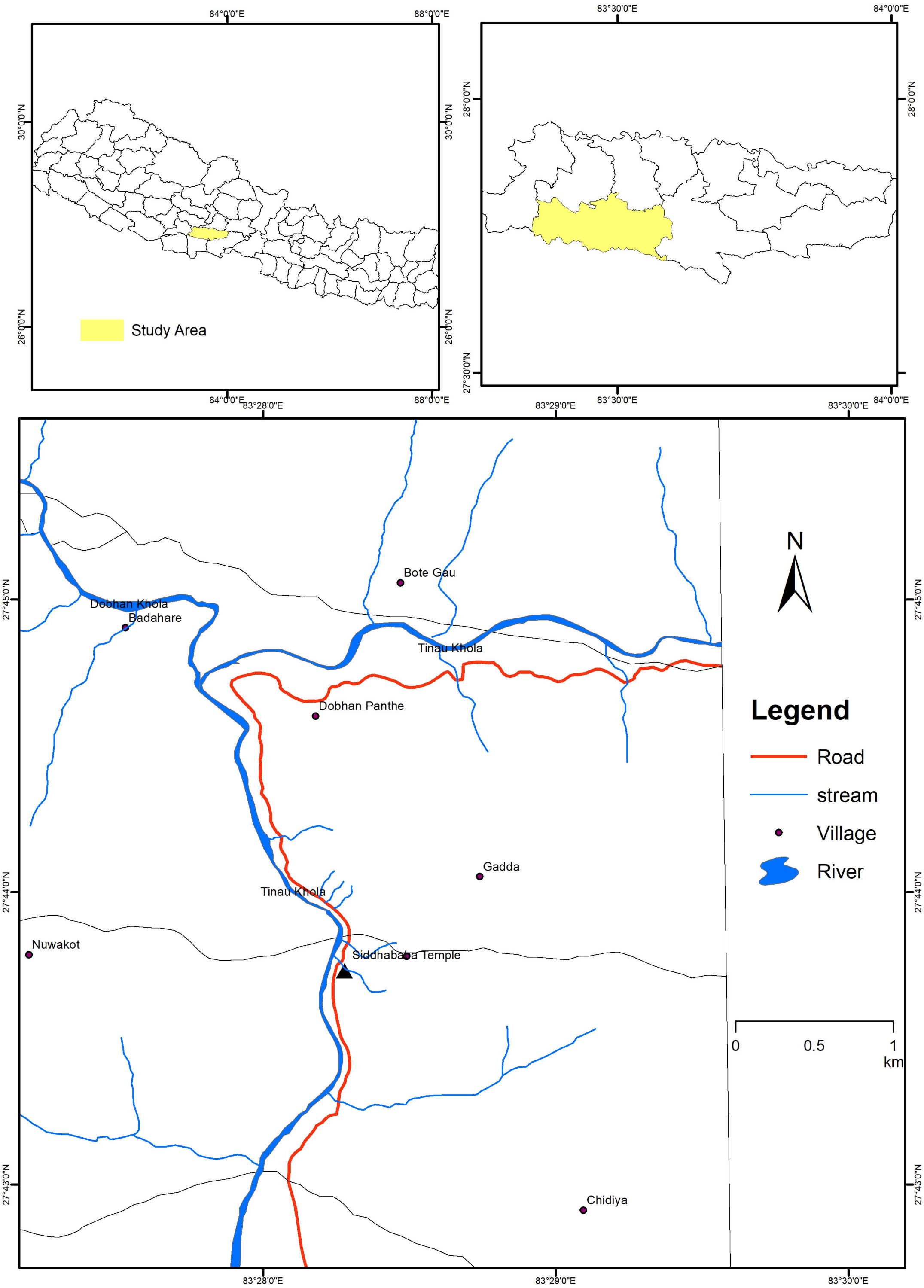
Figure 1
Location map of the study area



determination of the rock support for tunnel in the field, the parameters that are needed for the study.

The RMR developed by Bieniawski is the classification system based on six different parameters of rock. It assesses various parameters that include the compressive strength of intact rock material, the Rock Quality Designation (RQD), the spacing and condition of discontinuities, the groundwater conditions, and the orientation of discontinuities. The rating of each of these parameters is summarized in a numerical value to calculate RMR [6].

Originally developed by the Norwegian Geotechnical Institute, the Q-system for rock mass classification consisted of around 200 tunnel case histories, primarily from Scandinavia [7]. This system

Table 1
Rock mass classification based on Q-value and RMR value

Descriptions		Range of Q-values		Range of RMR values	
Rock class	Quality descriptions	Minimum	Maximum	Minimum	Maximum
Class I	Very good to excellent	100	1000	85	100
Class II	Good	10	100	65	85
Class III	Fair to good	4	10	56	65
Class IV	Poor	1	4	44	56
Class V	Very poor	0.1	1	35	44
Class VI	Extremely poor	0.01	0.1	20	35
Class VII	Exceptionally poor	0.001	0.01	5	20

is a numerical assessment of the quality of the rock mass, consisting of six parameters, used to estimate tunnel support. Grouped into three quotients are the six parameters: RQD, number of joint sets (Jn), roughness of the most unfavorable joint or discontinuity (Jr), degree of alteration or filling along the weakest joint (Ja), water inflow (Jw), and stress condition given as the stress reduction factor (SRF). This grouping provides an overall assessment.

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF} \tag{1}$$

The classification system of rock mass based on RMR [8] and Q-value [7] is classified in rock mass class on the basis of Q-value and RMR value which is tabulated in Table 1.

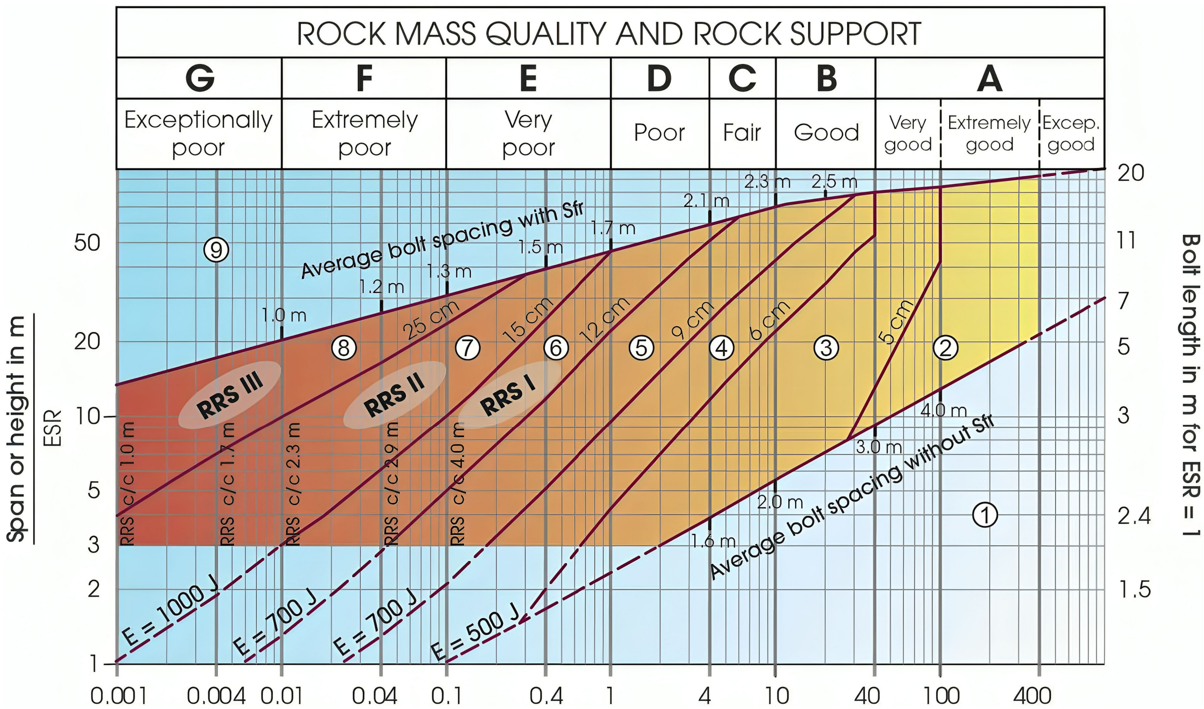
The first introduced rock slope kinematic analysis was performed without the consideration of shear strength and resistance in the rock slope [9, 10]. Different types of failures such as wedge failure and plane failure are determined with the help of kinematic analysis. Wyllie and Mah [11] have defined a condition for wedge failure, plane failure, and toppling failure based on which the analysis is done.

The Q-system chart mentioned in Figure 2 is used to develop the support system based on Q-value. Similarly, rock classification and support system designed by Bieniawski for RMR value are mentioned in Table 2.

Various computer software such as GIS, AutoCAD, and Illustrator were used for mapping and preparing route maps. MS Word was used for report writing, and MS Excel was used for data calculation. Dips were used for slope stability analysis.

Data collected from the fieldwork are then organized and analyzed. In this process, raw data were obtained and converted it into information useful for decision-making.

Figure 2
The Q-system chart for rock support estimate, developed by the Norwegian Geotechnical Institute [12]



3. Geology and Engineering Geology

Geological study of the Tinau Khola section has been conducted [13]. But, the lithostratigraphy of the area established by [13] has been adopted in this study (Figure 3). The proposed road tunnel has passed in the rocks of the Lower and Middle Siwaliks. The Lower Siwaliks are composed of thick to thin-bedded shale, mudstone, and sandstone, whereas the Middle Siwaliks are represented by the presence of friable, pepper and salt appearance: sandstone and gray shale. Differential weathering pattern is generally observed in the rocks of shale and sandstone of the Siwaliks [14, 15].

Engineering geological map (Figure 4) has been prepared based on the distribution of rocks and soil, landslide, and hydrogeological condition. A major dripping of water more than 5 ltr/sec is present with some minor dripping. Four landslides are identified along the road section. The study area lies in high rock fall risk zone, and

Table 2
RMR classification guide for excavation and support in rock road tunnels [8]

Rock mass quality description	Rock support (RS) class	Assigned tunnel rock support
Fair–good	RS III	25 mm dia., 3 m long systematic grouted rock bolts, at a spacing of 1.5 m × 1.5 m and 15 cm thick steel fiber shotcrete
Poor	RS IV	25 mm dia. 3 m long systematic grouted rock bolts at a spacing of 1.3 m × 1.5 m and 20 cm thick steel fiber shotcrete. Advance pre-injection grouting to control water inflow into the tunnel.
Very–poor	RS V	25 mm dia. 3 m long systematic grouted rock bolts at a spacing of 1.3 m × 1.3 m and 15 cm thick steel fiber shotcrete.
Extremely–poor	RS VI	25 mm dia. 3 m long systematic grouted rock bolts at a spacing of 1.2 m × 1.2 m and 20 cm thick steel fiber shotcrete. Steel ribs at a spacing of 1 meter to control plastic deformation. Advance pre-injection grouting is provisioned to control water inflow into the tunnel.
Exceptionally–poor	RS VII	25 mm dia., 3 m long systematic grouted rock bolts at a spacing of 1.1 m × 1.1 m and 20 cm thick steel fiber shotcrete. Steel ribs at a spacing of 1 meter to control plastic deformation.

Figure 3
Geological map of the study area modified after [13]

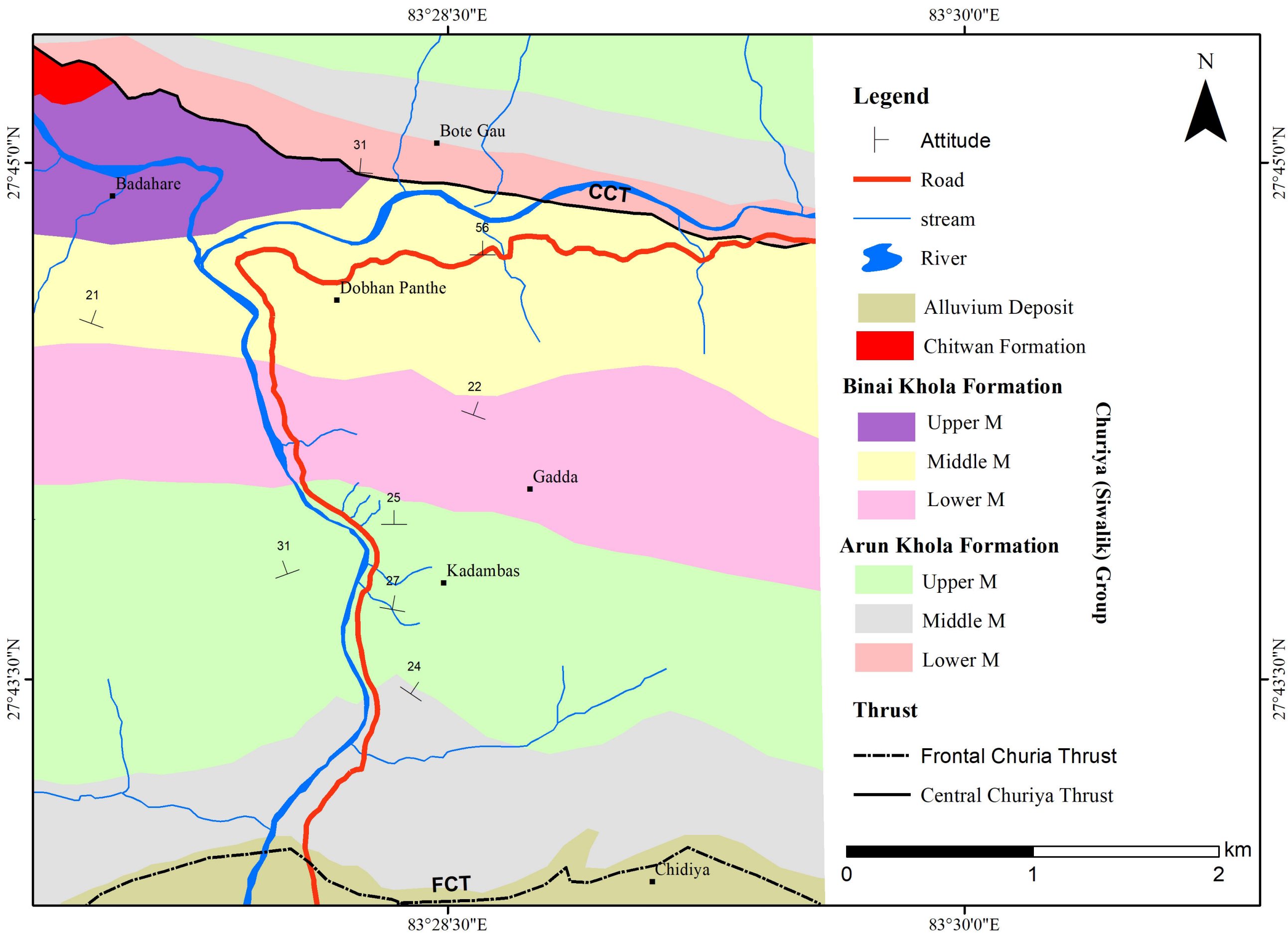
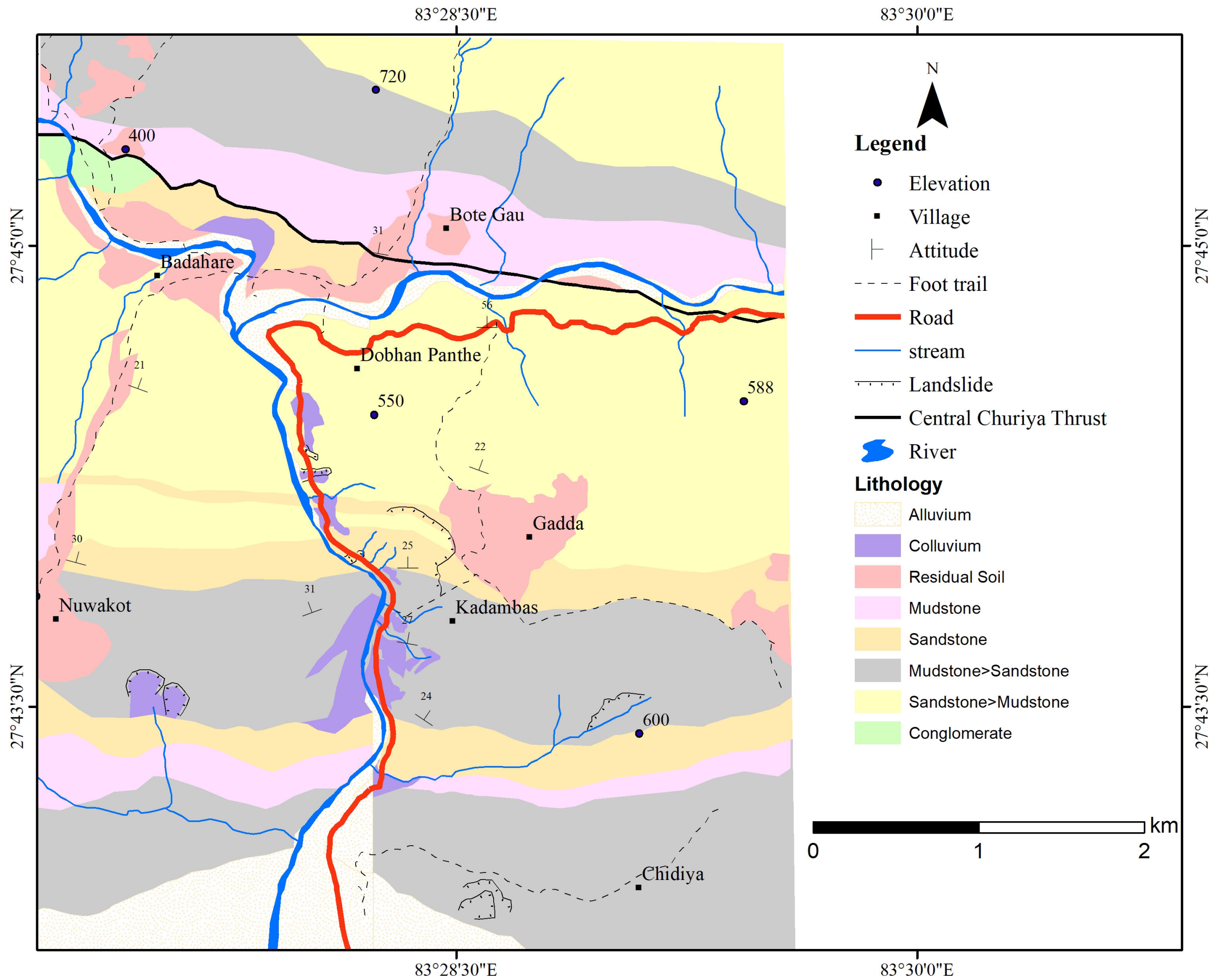


Figure 4
Engineering geological map of the study area



wedge failure and plane failure seem common in particular sections of this area. Interbedding of sandstone and mudstone has shown the differential weathering pattern which is a major reason of rock fall in this area.

4. Results

The study area is located in Palpa district along the Siddhartha Highway in between the chainage 29+000 to 30+370. Throughout the road tunnel alignment, sandstone and mudstone of the Lower Siwaliks and Middle Siwaliks constitute the main lithology which is shown in Route Map (Figure 5). The rocks exposed are jointed and moderately weathered. Three set of major joints with random joints were revealed at the study area. Based on the results of empirical classification based on RMR and Q-system, the rock exhibited poor rock to extremely poor rock (Table 3).

The proposed support system for the road tunnel alignment according to Q-system is rockbolt of 2 m length and 20 mm diameter placed with spacing of 1.6*1.6 c/c to 1.4*1.4 cc with shotcrete of 50 to 100 mm along crown and wall irrespective of their rock class. The support system according to RMR classification is rock bolt of 3 m length with 20 mm diameter placed within the spacing of 1 to 2 m with shotcrete of 50 to 150 mm according to their rock class.

Figure 6 shows the distribution of the rock mass along the tunnel road section with description of the support system (Table 4).

The support system based on RMR shows that 67 m of tunnel road needs 25 mm diameter 3 m long systematic grouted rock bolts at a spacing of 1.3 m × 1.5 m and 20 cm thick steel fiber shotcrete. 685 m of tunnel road needs 25 mm diameter 3 m long systematic grouted rock bolts at a spacing of 1.3 m × 1.3 m and 15 cm thick steel fiber shotcrete. And 385 m of tunnel road needs 25 mm diameter 3 m long systematic grouted rock bolts at a spacing of 1.2 m × 1.2 m and 20 cm thick steel fiber shotcrete. Steel ribs at a spacing of 1 meter for controlling plastic deformation. Advance pre-injection grouting is required to control water flow in the tunnel.

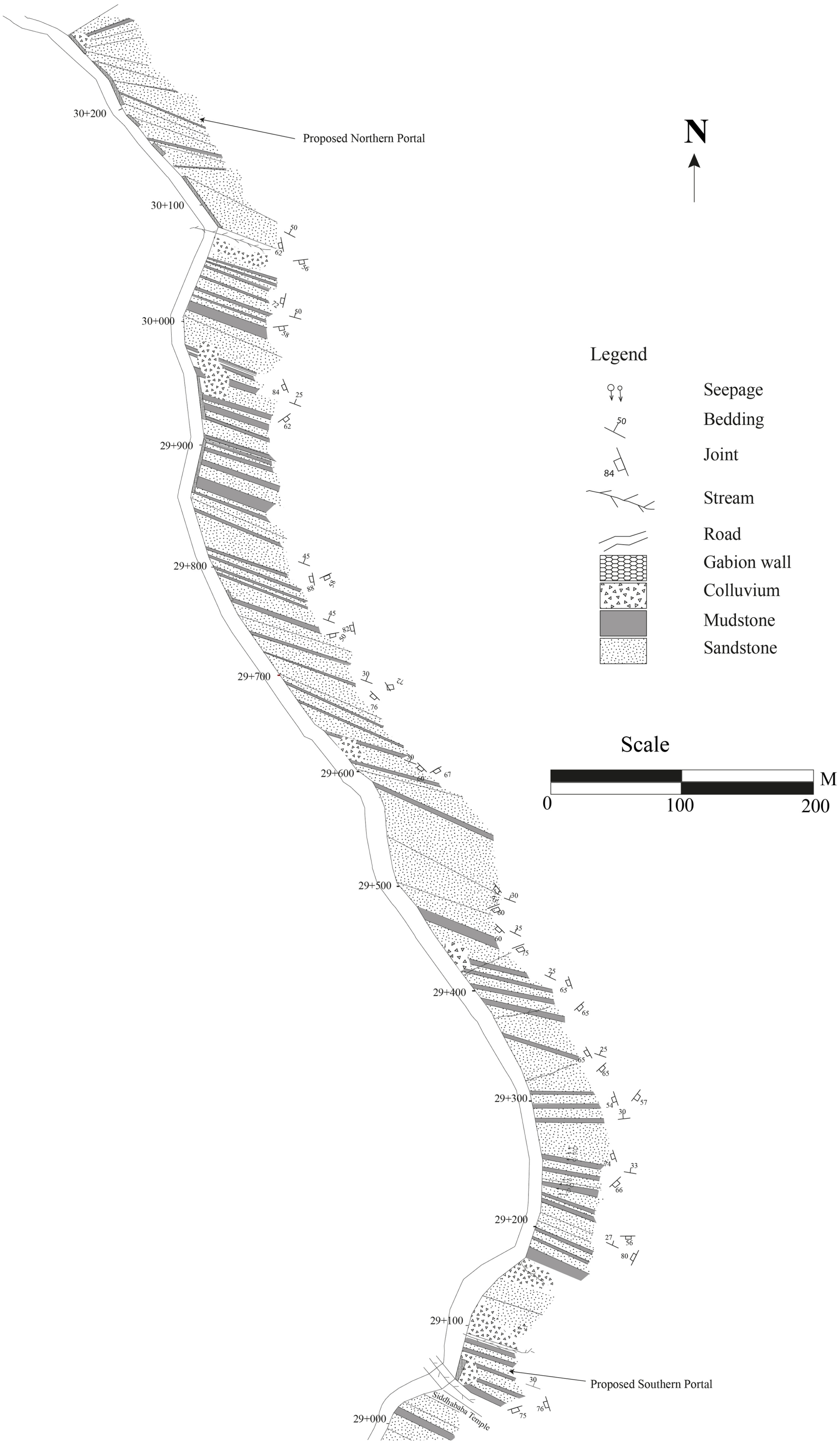
The planes and wedges formed by the planes were then analyzed with respect to the internal friction angle has been adopted as 30° for the stability calculation. Slope condition is analyzed using the observed bedding plane attitudes and their

Table 3
Rock mass classification

	Bedding		Discontinuities											
			Joint-1			Joint-2								
Chainage	Attitude	Alter-nation	Attitude	Spacing	Persistence	Attitude	Spacing	Persistence	RQD	UCS (MPa)	Hydrogeological condition	Joint water reduction factor	Q-value	RMR value
29+019 – 29+115	15/32	6	130/62	0.9m	2m	230/57	1.3m	4m	60	45	Minor_inflow, i.e.,< 5 l/m	1	0.67	40
29+115 – 29+228	0/30	8	240/76	1.1m	7m	150/74	0.7m	10m	25	50	Minor_inflow, i.e.,< 5 l/m	1	0.22	30
29+228 – 29+305	13/27	4	280/80	0.5m	7m	165/56	2m	10m	55	50	Minor_inflow, i.e.,< 5 l/m	1	0.89	43
29+305 – 29+351	358/33	8	240/74	0.5m	3m	128/66	2m	5m	45	55	Large inflow	0.5	0.19	29
29+351 – 29+400	340/31	8	240/54	2m	3m	112/57	1.5m	3m	40	60	Medium to large inflow	0.66	0.22	30
29+400 – 29+445	0/25	6	228/64	1m	4m	120/61	2m	10m	45	60	Medium inflow	0.66	0.34	34
29+445 – 29+550	13/25	6	245/64	0.4m	1m	125/72	0.6m	5m	40	45	Large inflow	0.5	0.22	30
29+550 – 29+585	7/35	6	213/60	2m;	4m	140/75	3m	7m	60	50	Medium Inflow	0.66	0.42	36
29+585 – 29+620	5/31	4	240/65	0.5m	8m	151/59	2m	7m	45	45	Medium Inflow	0.66	0.51	38
29+620 – 29+672	5/30	6	210/61	0.9m	2m	140/67	1.5m	2m	65	45	Minor_inflow, i.e.,< 5 l/m	1	0.74	41
29+672 – 29+744	13/30	4	230/71	0.7m	2m	155/72	1m	4m	55	50	Minor_inflow, i.e.,< 5 l/m	1	0.94	43
29+744 – 29+773	5/31	6	215/76	0.5m	5m	165/72	1m	7m	55	50	Medium inflow	0.66	0.39	36
29+773 – 29+824	7/45	6	250/88	1m;	2m	148/50	1m	2.5m	55	45	Minor_inflow, i.e.,< 5 l/m	1	0.59	39
29+824 – 29+830	10/45	8	248/88	0.4m	2m	140/58	1.5m	3m	45	40	Minor_inflow, i.e.,< 5 l/m	1	0.39	36
29+830 – 29+950	5/30	4	245/60	0.2m	3m	180/78	1.3m	2m	65	50	Medium inflow	0.66	0.73	41
29+950 – 30+020	20/26	6	235/84	0.7m	0.9m	130/62	1.4m	3m	60	55	Minor_inflow, i.e.,< 5 l/m	1	0.67	40
30+020 – 30+105	0/56	6	267/72	1m	2m	167/58	0.7m	3m	65	45	Minor_inflow, i.e.,< 5 l/m	1	0.74	41
30+105 – 30+172	8/42	4	250/62	0.6m	3m	155/56	0.4m	4m	65	70	Minor_inflow, i.e.,< 5 l/m	1	1.11	45
30+172 – 30+200	0/39	6	255/68	0.4m	1m	125/58	0.7m	2m	65	50	Medium inflow	0.66	0.74	41
30+287 – 30+370	5/38	6	245/54	0.5m	3m	130/33	0.8m	3m	60	50	Minor_inflow, i.e.,< 5 l/m	1	0.7	41

*RQD = Rock Quality Designation; UCS = Uniaxial compressive strength

Figure 5
Route map of the study area



conditions at different locations. All the above-mentioned analyses were done using Geotechnical Software Dip 6.0. The slope stability condition along the tunnel alignment seems to be more or less same. The dip direction and of the bedding plane ranges from 000 to 026 and dip amount 20 to 45 degrees. The kinematic analysis indicated the potential of wedge failure at the southern portal of road tunnel whereas toward the northern portal with abundance of sandstone has low potential failure. Beyond the southern portal area between the chainage 28+800 to 29+090 along the road section, plane failure seems likely whereas the

Table 4
Rock mass description along tunnel alignment

Chainage	29+090 – 29+115	29+115 – 29+228	29+228 – 29+305	29+305 – 29+351	29+351 – 29+400	29+400 – 29+445	29+445 – 29+550	29+550 – 29+585	29+585 – 29+620	29+620 – 29+672
Rock Type	MST	MST>>SST	MST, SST	SST	MST	SST, MST	SST, MST	MST	SST	SST
Weathering	Moderate	Moderate	Highly	Moderate	Highly	Moderate	Slightly	Slightly	Slightly	Slightly
RMR Values	37	30	43	29	30	34	30	36	38	41
Rock Mass classification	V	VI	V	VI	VI	VI	VI	V	V	V
Q-values	0.45	0.22	0.89	0.19	0.22	0.34	0.22	0.42	0.51	0.74
Rock Mass classification	V	V	V	V	V	V	V	V	V	V
Support class	RSV	RSVI	RSV	RSVI	RSVI	RSVI	RSVI	RSV	RSV	RSV

Chainage	29+672 – 29+744	29+744 – 29+773	29+773 – 29+824	29+824 – 29+830	29+830 – 29+950	29+950 – 30+020	30+020 – 30+105	30+105 – 30+172	30+172 – 30+200
Rock Type	SST>>MST	SST	MST	MST	SST	SST	MST, SST	SST	SST
Weathering	Slightly	Moderate	Moderate	Highly	Moderate	Slightly	Moderate	Moderate	Moderate
RMR Values	43	36	39	36	41	40	41	45	35
Rock Mass classification	V	V	V	V	V	V	V	IV	V
Q-values	0.94	0.39	0.59	0.39	0.73	0.67	0.74	1.11	0.37
Rock Mass classification	V	V	V	V	V	V	V	IV	V
Support class	RSV	RSV	RSV	RSV	RSV	RSV	RSV	RSIV	RSV

*MST, SST, represents mudstone and sandstone in the Table

northern part from the northern portal chainage from 30+200 to 30 +600 has potential toppling failure. Joint distribution along the tunnel alignment is shown in Figure 7, and the representative kinematic analysis for different location is shown in Figure 8.

5. Discussion

The results of this study have valuable insights into the geological conditions and rock mass characteristics in the Lower and Middle Siwaliks region of Nepal which is relatable to the youngest mountain chain in the Himalaya belt that is extended from northeast India through Nepal to northwest India and northern part of Pakistan with abundance of mudstone and sandstone rock mass. The geological diversity of the study area has significant challenges in the construction of tunnel.

The study area covers part of the Arung Khola formation with the lithology of Lower Siwaliks and Middle Siwaliks [13]. The rock of the Arung Khola Formation is composed of alternating layer of sandstone and mudstone. Generally, differential weathering pattern is seen in these rock types, creating weak planes that can be sheared easily due to overloading of sandstone bed on mudstone bed.

For the rock mass classification and support system, Q-system [7, 16] and RMR system [6, 8] were used which has wide range of application in rock mechanics; however, these system are highly established worldwide for tunnel support, due to its continuous update in terms of rock characterization and support system [17].

In context of Nepal, Q and RMR systems are extensively used for the tunnel support, particularly in hydropower sector of Nepal [18]. Similarly, this study uses these systems for rock mass classification and support system.

The Q-value is calculated to be in range between 0.19 to 1.04 and 0.39 to 1.11 in the Lower Siwaliks and Middle Siwaliks, respectively. The value shows that the Rock mass class falls under rock mass class V and rock mass class IV. Class V represents very poor rock, whereas class IV represents poor rock. The value obtained from RMR is classified into extremely poor to poor rock.

Wyllie and Mah [11] have described the condition for the failure to occur according to which kinematic analysis in each section was interpreted. Southern portal of road tunnel seems more vulnerable to wedge failure, where the presence of mudstone is larger than sandstone. The possibility of plane failure can be seen at the beginning of the chainage and toward the ending of chainage, and the possibility of occurrence of toppling along the joint is more likely.

Similar studies carried out along the Siddhartha Highway have also identified potential plane failure and wedge failure [4, 5, 19] which confirms the consistency of such geological conditions within the region.

Bhandari and Dhakal [20] found out highly fragile alternate bed of sandstone and mudstone and performed kinematic analysis in the Siwalik zone of Babai River catchment area, where they found flexure toppling and wedge failure predominant. This study suggests similar findings of alternation of sandstone and mudstone with wedge failure most common; however, plane failure was more common than flexure toppling failure.

Studies of [21] in the Lesser Himalaya of Central Nepal and [22] in sub-Himalaya region along Muzzaffarabad-Nelum road found poor to fair rocks which is consistent with the values observed in our study. These findings highlight the challenging conditions for rock tunneling in Himalayan range.

Dhang [23] in the geotechnical investment of Udhampur railway tunnel in Jammu and Kashmir area found poor to very poor (q-value ranging 0.05–2, and RMR 20–40) in the rock mass

Figure 6
Rock mass profile along road tunnel alignment

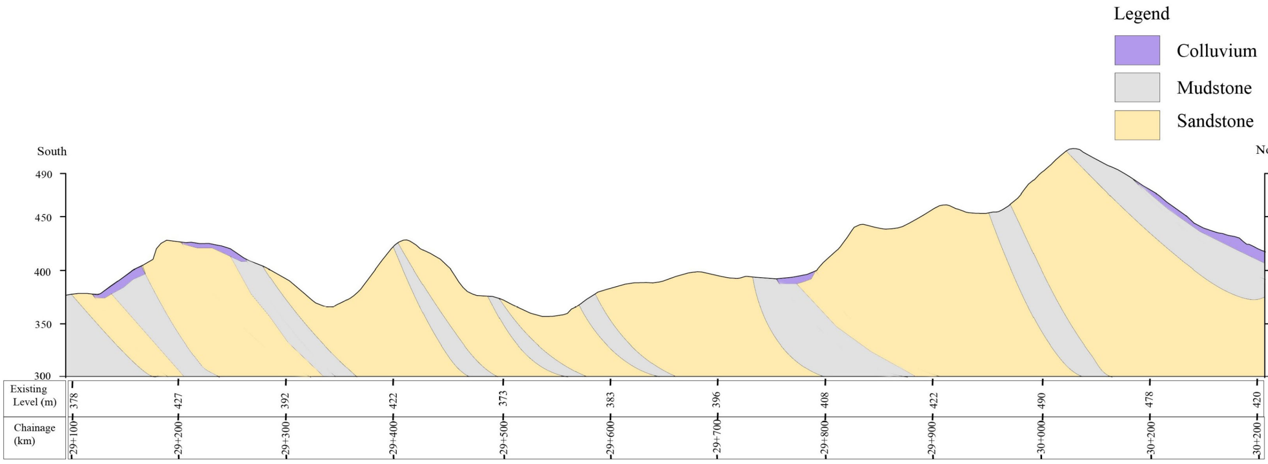
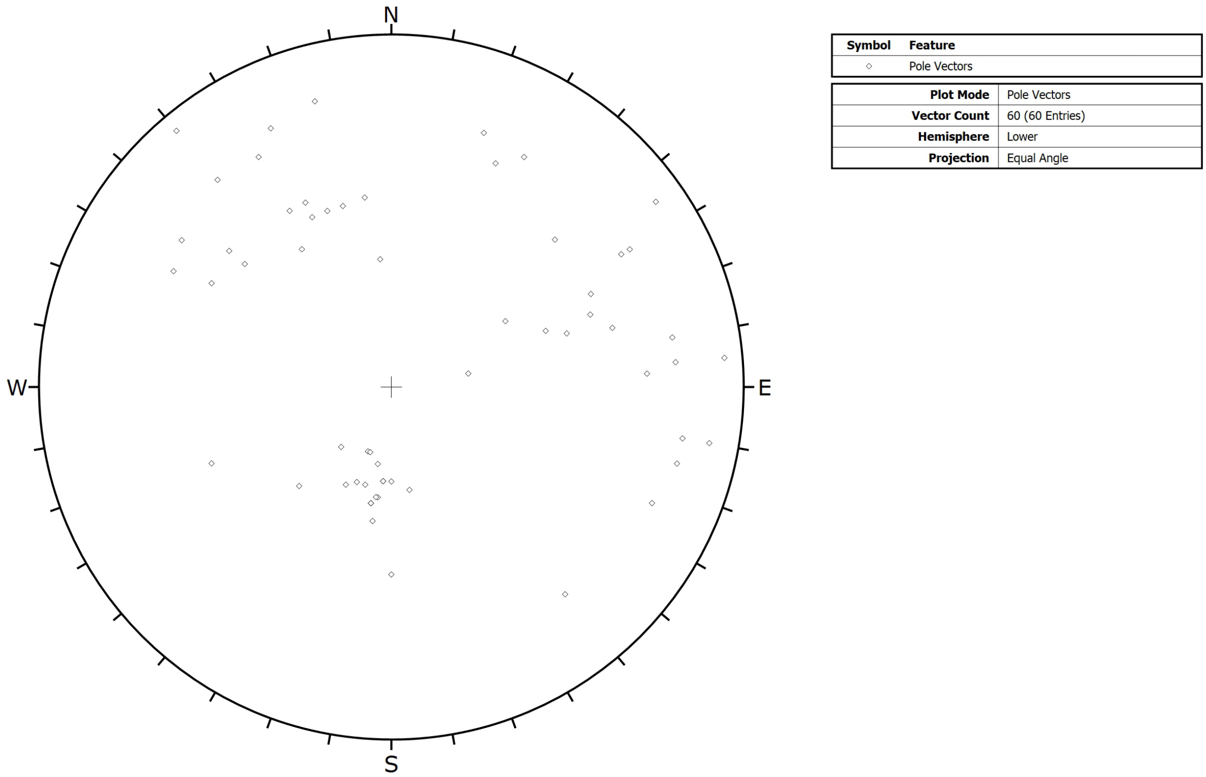


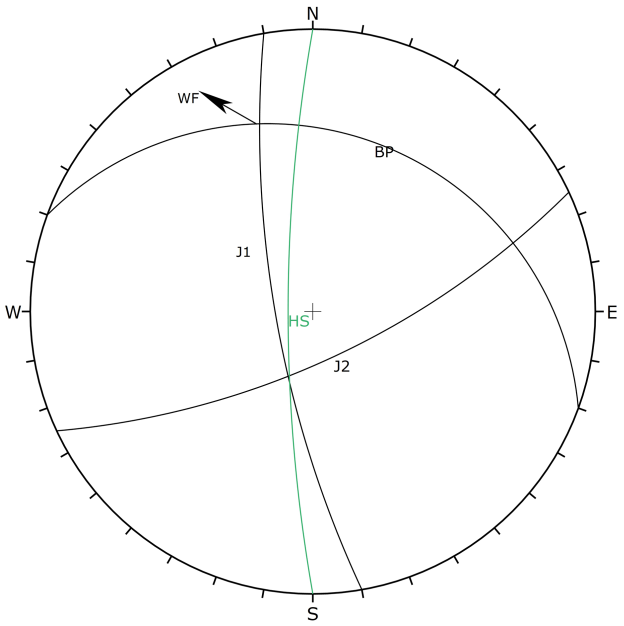
Figure 7
Joint distribution along tunnel alignment



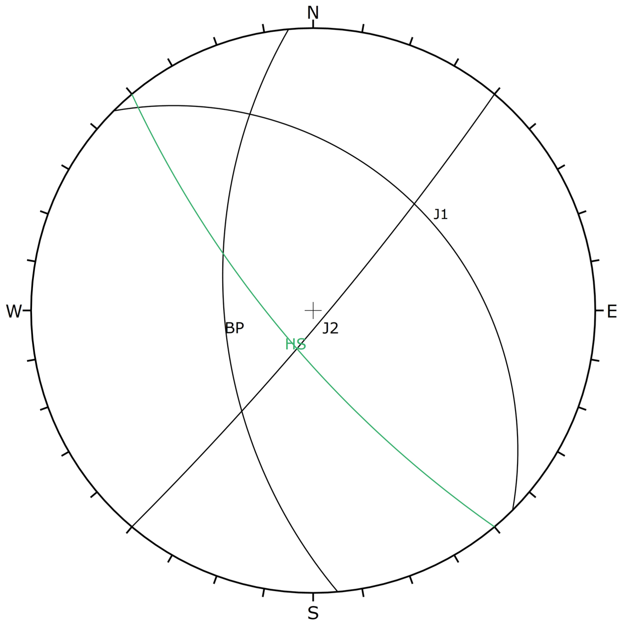
of sub-Himalaya region which is in similar range to our study; however, NATM approach was used for tunnel support designing while our study uses Q-system and RMR system as it is suggested of the best approach for preliminary support design [24].

This study provides crucial insights into the geological conditions and rock mass behavior in the Lower and Middle Siwaliks region, which have significant implications for tunnel construction. The rock mass classification and kinematic analysis underscore the challenges involved in tunneling projects in this area. By comparing these results with other studies in the region, we gain a broader understanding of the geological complexities and can inform engineering decisions for future tunneling endeavors in similar geological settings. Additionally, the findings of this study contribute to the growing body of knowledge on

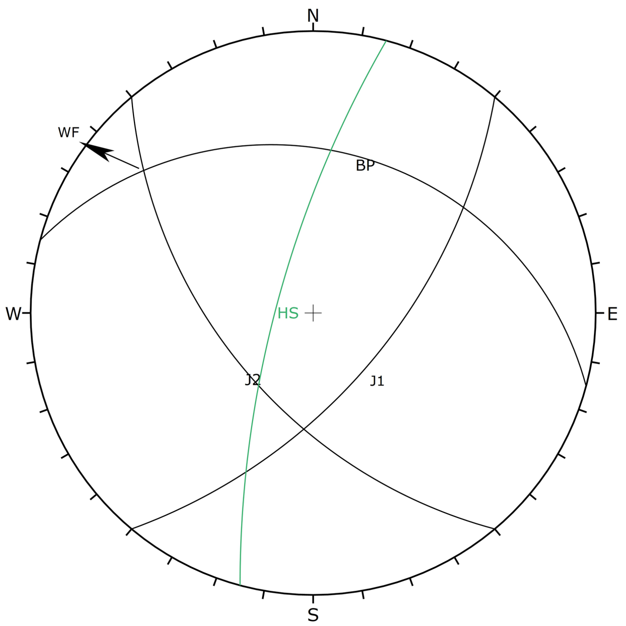
Figure 8
Kinematic analysis in different chainage of road section



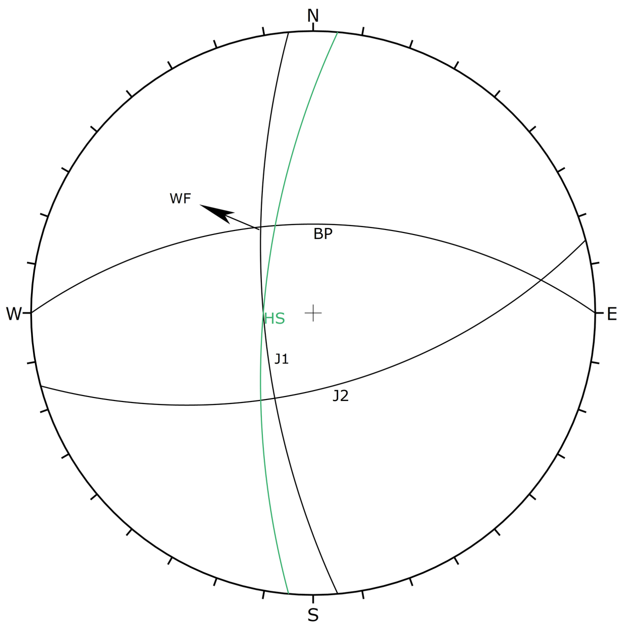
A. Southern portal



B. Northern portal



C. Chainage at 28+410



D. Chainage at 30 +430

rock mechanics and engineering geology, benefiting readers interested in geological studies and tunneling projects.

6. Conclusions

Throughout the road tunnel alignment, sandstone and mudstone of the Lower Siwaliks and Middle Siwaliks constitute the main lithology. The rocks exposed are jointed and moderately weathered. Three major joints sets with random joints were revealed at the study area. Based on the results of empirical classification based on RMR and Q-system, the rock exhibits poor rock to extremely poor rock. The RMR value ranges between 29 and 45 and Q-value ranges between 0.19 and 1.11. The kinematic analysis indicated the potential of wedge failure at the southern portal of road tunnel whereas toward the northern portal with abundance of sandstone has low potential failure.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

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