19th WORLD CONFERENCE OF THE ASSOCIATED RESEARCH CENTRES FOR THE URBAN UNDERGROUND SPACE
Belgrade, Serbia, November 4-7, 2025.

ACUUS BELGRADE 2025

Paper No: 2.12.114
DOI: 10.46793/ACUUS2025.2.12.114

CHALLENGES ASSOCIATED WITH PLANNING AND CONSTRUCTION OF A ROAD TUNNEL THROUGH LESSER HIMALAYAN ROCK MASS – A CASE STUDY

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Abstract: Tunneling is crucial in infrastructure development, including hydropower, irrigation, water supply, sewerage, and transportation sectors. However, these underground projects are often accompanied by uncertainty and risk, particularly concerning stability and safety. The Himalayan region, characterized by relatively young tectonics, varying geological conditions, and fractured rock mass, is prone to challenges associated with block falls and stress-induced instabilities. Several factors, including lithology, rock mass conditions, structural geology, in situ stress conditions, groundwater conditions, tectonic activities, and topography, influence the utilization of underground space. This study aims to understand and evaluate the behavior of the surrounding rock mass of a proposed road tunnel intended to connect the second-largest city, Pokhara, with the Kaligandaki Corridor. The proposed road tunnel traverses the Lesser Himalayan geological formation in central Nepal. The ground behavior has been characterized using Rock Mass Rating (RMR) and the Q-system of rock mass classification. In addition, stability conditions have been evaluated using both analytical and numerical approaches for various rock formations where varying rock mass quality and rock cover prevail. The majority of the tunnel stretch is characterized by poor-quality rock mass. The analysis identified wedge failure in the phyllite with intercalation of bands of metasandstone at the eastern portal. These conditions necessitate the implementation of stabilization measures consisting of systematic rock bolting and steel fiber shotcrete. Furthermore, some sections with highly schistose and fractured rock mass exhibited squeezing behavior, with the highest tunnel strain of 15.01%, indicating the need for specialized support measures to accommodate the anticipated ground deformation.

Keywords: Tunneling, Lessor Himalaya, Rock mass quality, Ground behavior, Stability, and safety

1. INTRODUCTION

According to Panthi (2006), tunneling technology in Nepal has potential applications in multiple domains such as hydropower, transportation, irrigation, water supply, and storage facilities. However, the majority of tunnels constructed to date have been developed in the energy sector, with comparatively limited applications in other domains. Nepal's mountainous terrain, uneven topography, dynamic monsoon, and rock mass influenced by deep weathering conditions necessitate extensive cut slope stabilization and retaining structures for surface construction works, including roads, leading to higher construction and maintenance costs. Thus, it is difficult to establish " sustainable transport with high mobility, safety, and comfort" (JICA, 2019). The challenging topography of steep and unstable mountainous terrain imposes the adoption of tunneling solutions to enable shorter and more efficient transportation routes, while minimizing environmental disturbance (Panthi, 2006). Tunnel construction offers a direct and safer route, significantly reducing travel time and improving regional connectivity, thereby facilitating the efficient movement of goods and services. In recent years, Nepal has made notable progress in the development of its transportation infrastructure with the inclusion of road tunnels such as the Nagdhunga road tunnel, Siddhababa road tunnel, and twin-tube tunnels at the Kathmandu-Terai Fast Track Road projects.

Tectonically, the Himalayan region is characterized by a highly dynamic geological setting. The ongoing compressional tectonic deformation and active reverse faulting mechanism contribute to the accumulation of rock stresses as well as distressing conditions. As a result of active tectonic processes and intense, prolonged monsoon

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rains, the rock mass in the Himalayas is generally weathered and fractured near the surface, while schistose, deformed, and faulted at depth. Hence, planning, design, and construction of tunnels and caverns in this region have always been challenging. As a result, instability issues such as plastic deformation, rock burst, tunnel collapses, and water ingress are common in tunneling in the Himalayas (Panthi and Nilsen, 2007; Panthi, 2012; Dwivedi et al, 2013; Shrestha, 2014; Basnet et al., 2014).

Stability and safety are fundamental considerations in tunneling, especially in the context of transportation infrastructure. Road tunnels constructed through challenging terrain, such as mountains and urban environments, require careful design to ensure long-term structural integrity and serviceability. Despite careful planning, underground construction is often accompanied by numerous challenges, primarily associated with geological uncertainties and their implications for tunnel stability. To effectively address these issues, it is imperative to acquire detailed geological and geotechnical information during planning, design, and construction of a tunnel project (Panthi and Nilsen, 2007). A comprehensive understanding of the surrounding rock mass behavior, the selection of appropriate construction techniques, and the performance evaluation of support systems are essential for the successful execution of tunneling projects (Zhang et al., 2025). Hence, identifying and assessing potential failure mechanisms based on rock mass characteristics is especially crucial during planning and design phases. Such insights enable the formulation of initiative-taking strategies and mitigation measures that ensure tunnel stability.

To assess deformation at the tunnel periphery during excavation and to design suitable support measures required, various analytical and numerical simulation methods have been developed over the years (Carranza-Torres and Fairhurst, 2000; Vlachopoulos and Diederichs, 2009; Su et al., 2021) . In recent decades, the integration of advanced construction and monitoring technologies, as well as numerical modeling techniques, has significantly enhanced the ability to predict and manage tunnel behavior.

This study aims to conduct an overall geological assessment and perform stability analyses of selected sections of the proposed road tunnel alignment along the Baglung-Pokhara highway, which connects the Kaligandaki corridor with the second-largest city, Pokhara. The tunnel alignment traverses through varying rock mass quality and overburden conditions. The analyses employ both analytical and numerical modeling approaches to assess the stability conditions of a 14 km long road tunnel proposed to traverse through Lesser Himalayan rocks. The existing 38 km long stretch of Pokhara Baglung Highway, Hemja (Kaski) to Patichaur (Parbat), traverses through steep topography with challenging Himalayan mountainous terrain. The proposed road tunnel will reduce the road length to 14 km and will serve as a strategic segment that will connect Pokhara with the Kaligandaki corridor, which is under construction, and will help to enhance cross-border trade and mobility between Nepal, India, and China.

2. REGIONAL AND SOCIOECONOMIC SETTING

The Baglung Pokhara Highway connects the Kaligandaki Corridor. The 38 km stretch from Hemja Pokhara (Kaski) to Patichaur (Parbat) passes through steep topography and challenging geological conditions. The proposed 14 km road tunnel will replace a 38 km-long, meandering road. The development of this road tunnel will significantly enhance regional and cross-border trade by shortening the existing road length that traverses steep terrain with several sharp bends. This shortening will reduce travel distance, travel time, and transportation cost. In addition, road alignment will serve as a strategic connection between the city (Pokhara) and the Kaligandaki Road Corridor. The under-construction 445 km long Kaligandaki Road Corridor (Kantipur Post, 2025) will function as a land bridge between China and India by connecting the Korala border at Tibet, China, to the north and the Sunauli border with Northern India to the south. This will enable smoother movement of goods such as agricultural and industrial products, as well as local consumer items. At the same time, it will enable to establish of satellite cities and towns connecting the city, Pokhara, which will enhance domestic trade among the agrarian districts of Kaski, Parbat, Myagdi, and Mustang, allowing farmers to access larger city markets more efficiently. Furthermore, being the Mustang district a tourist destination, the improved (shortened) road will substantially improve connectivity, supporting tourism-driven trade. This is because the faster travel to tourist destinations like Jomsom and Mustang encourages greater flows of visitors, thereby expanding local markets for hospitality, handicrafts, and cultural products.

3. PROJECT DESCRIPTION

The proposed road tunnel project is expected to shorten the existing road from 38 km to 14 km. Entry and exit portals of the tunnel are planned to be located at 28°17.434' N, 083°52.568' E and 28°16.489' N, 083°44.607' E, respectively (Figure 1). The eastern entry portal is proposed at an elevation of 1167 m at Hemja, Kaski District, near Ghatte Khola (16 km northwest of Pokhara). The western exit portal is proposed at an elevation of 912 meters.

The tunnel alignment traverses hilly terrain with significant elevation variation, ranging from 900 m to 2050 m above mean sea level (amsl).

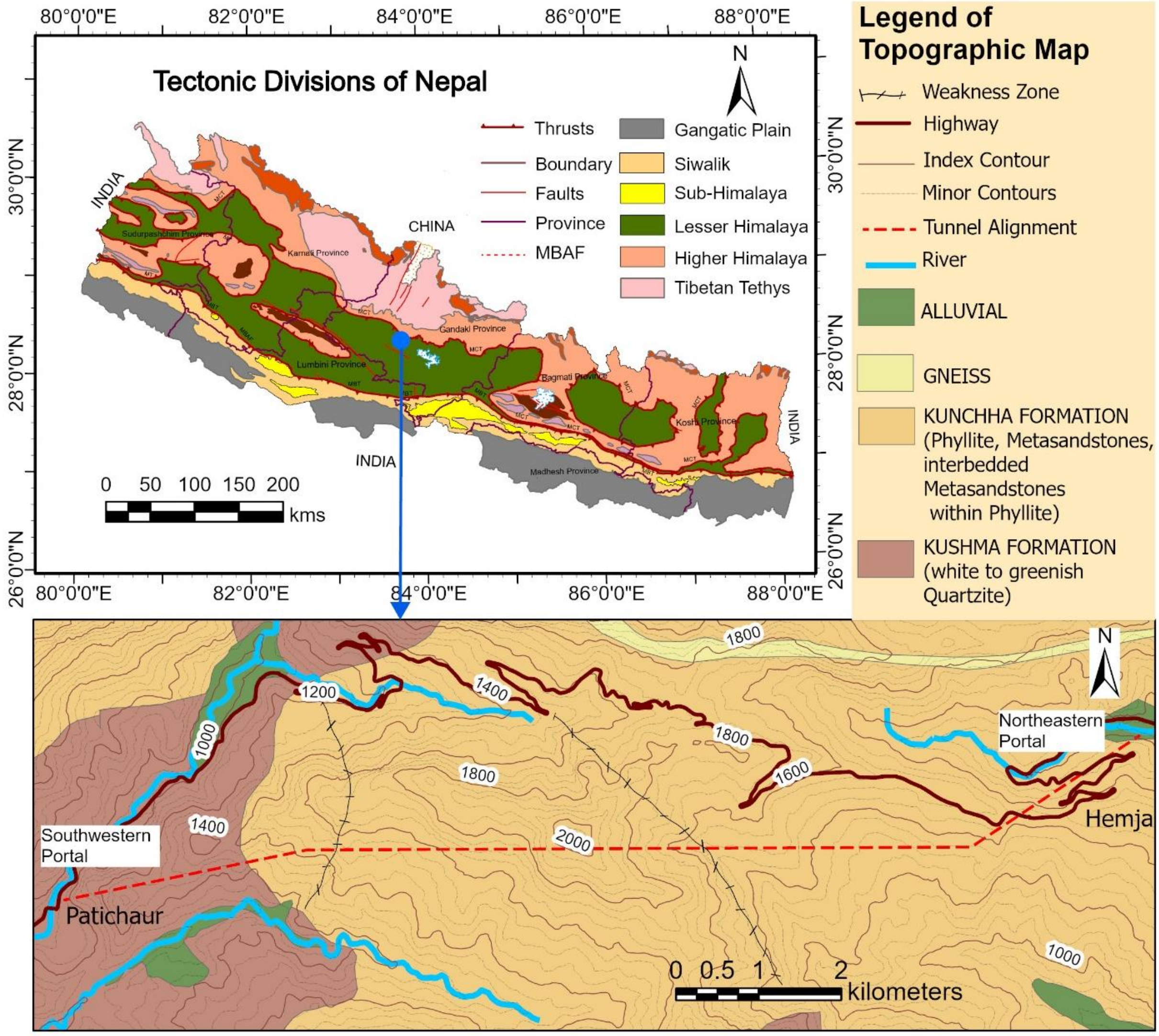


__Figure 1.__ Regional geological map with tunnel alignment (modified on Geological Map of Nepal, Department of Mines and Geology, 2023)

4. ENGINEERING GEOLOGICAL CONDITIONS

4.1. Geological formation

The proposed road tunnel alignment traverses the Lesser Himalaya Sequence, which is a geologically complex region situated between the Siwalik zone to the South and the Higher Himalaya zone to the North (Figure 1). Tectonically, this zone is bounded by two major thrust systems: the Main Boundary Thrust (MBT) in the south and the Main Central Thrust (MCT) in the north. Both tectonic faults have played a significant role in the Himalayan orogeny, contributing extensive deformation to the rock mass. Notably, the MBT remains tectonically active, resulting in deformed, faulted, folded, sheared, jointed, and weathered rock mass conditions along the alignment. The area is influenced by numerous major thrust faults located nearby, such as the Phalebas thrust and the Barigad fault in the west, which show signs of lateral movement. The area consists of low to medium-grade metamorphic rocks, which are intruded by higher-grade crystalline nappes and klippen (Upreti, 1999). The tunnel alignment intersects two major lithostratigraphic units consisting of the Kushma Formation (Ku) and the Kunchha Formation (Kn). These formations are predominantly composed of greenish-grey, medium-foliated, moderately weathered phyllite; white to yellow, greenish, fine-grained quartzite; and metasandstone interbedded with phyllite rocks. These rocks are famously known in the Lesser Himalayas of Nepal for their variable mechanical behavior under tunneling conditions (Sapkota & Paudel, 2018).

4.2. Rock mass condition

Required observations and measurements of the rock mass were conducted by the authors during multiple field visits to the project area. Various locations were selected based on the rock types, outcrop extent, rock-cut surfaces, and prevailing topography. Field investigations revealed that the exposed rocks predominantly consist of metasandstone to quartzite of a greenish-white color, exhibiting a fine to medium-grained crystalline texture and medium to thick-bedded structures at the southwestern exit portal near Patichaur, which belongs to the Kushma Formation (Figure 1). Joint persistence ranges from 3-10 meters with joint apertures between 1-5 mm commonly filled with silt/sand. The majority of outcrops in this area are slightly to moderately weathered and exhibit features of medium-grade metamorphism. In contrast, the northeastern entry portal (Figure 1), planned to be located within the Kunchha Formation, exposes lithologies composed mainly of deformed, fine to medium-grained, light grey phyllite, frequently intercalated with bands of metasandstone. The zone is characterized by intense fracturing and structural disturbance, which reflects significant tectonic deformation.

A field mapping was conducted during the dry season. The presence of lichens and vegetative growth along joint surfaces suggested seasonal moisture ingress, which is due to water seepage during the monsoon, indicating potential for damp to wet conditions in the rock mass. Furthermore, divergent dip directions of the foliation planes combined with anticline and syncline structures point to the presence of large-scale folding. The area has numerous local faults and folds that indicate intense tectonic activity, which is typical in the Lesser Himalayan region.

A notable tectonic fracture zone between the boundary of metasandstone and graphitic phyllite was encountered near Bhadaure (at 28°17'3.71"N, 83°48'44.06"E) of Kaski district. This fracture zone is projected to intersect the tunnel alignment at an approximate chainage of 5+000 m (Figure 2). The zone comprises crushed and highly fractured rock mass with reduced strength and stiffness, presenting a challenging segment for tunnel construction.

4.3 Rock mass quality characterization

The rock mass quality along the tunnel alignment was assessed using both RMR (Bieniawski, 1973) and Q system (Barton et al, 1974) of rock mass classifications. These classification methods are user-friendly and practical, which are widely used in Nepal and elsewhere. The Q system incorporates the Stress Reduction Factor (SRF) and thus gives a better assessment of the rock mass response to in situ stress conditions. In addition, the Q system directly links the rock mass quality class and allows us to estimate preliminary rock support measures, which is particularly valuable for tunnel design. On the other hand, the RMR system provides correlation to standup time and can be used to cross-check and validate the results obtained from the Q system. The rock mass quality along the tunnel alignment varies from extremely poor to good quality rock mass class (Table 1). All relevant parameters, such as discontinuity conditions, spacing, groundwater conditions, and rock strength, were evaluated through detailed field mapping. The RMR values along the tunnel alignment range from 31 to 77. Similarly, the Q-values varied significantly, ranging from as low as 0.01 (extremely poor rock mass class) to a maximum of 11.56 (good rock mass class). Both classification methods indicate substantial heterogeneity in rock mass quality across the tunnel alignment (Table 1 and Figure 2). Extremely poor-quality rock mass class is associated with highly sheared, folded, and weathered phyllitic zones, while fair to good-quality rock mass corresponds to relatively massive and intact metasandstone and quartzite units.

Table 1. *Rock mass quality description along the tunnel length*

Chainage of the tunnel	RMR values	Q values	Rock class	Quality
From 0+000 to 4+939	53-56	1-4	IV	Poor
From 4+940 to 5+000	31	0.01	VI	Extremely Poor
From 5+001 to 9+749	65-77	10.56-11.56	II	Good
From 9+750 to 9+850	31-35	0.02-0.04	VI	Extremely Poor
From 9+851 to 11+199	52-55	1.21-3.11	IV	Poor
From 11+200 to 13+500	60-65	4.17-10	III	Fair to good

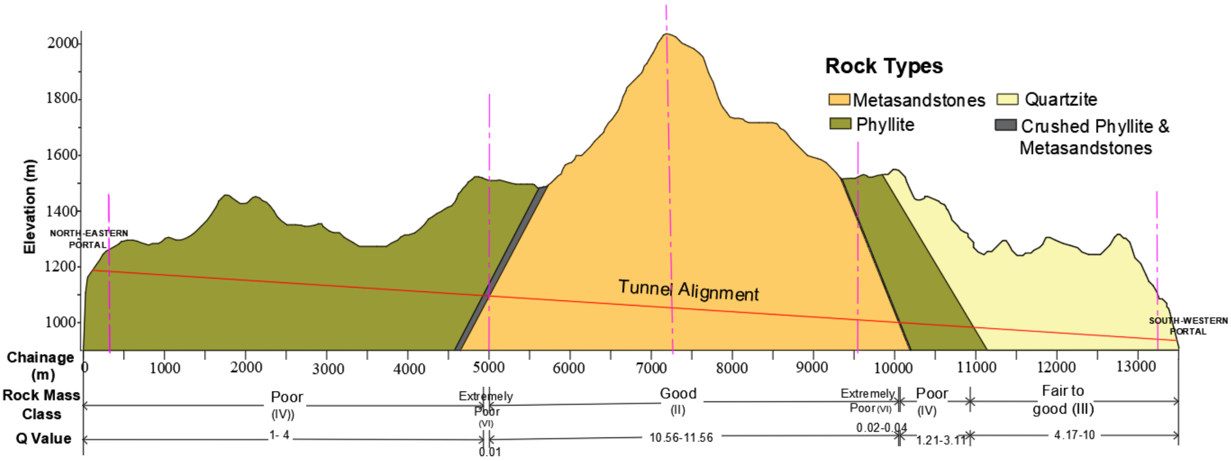
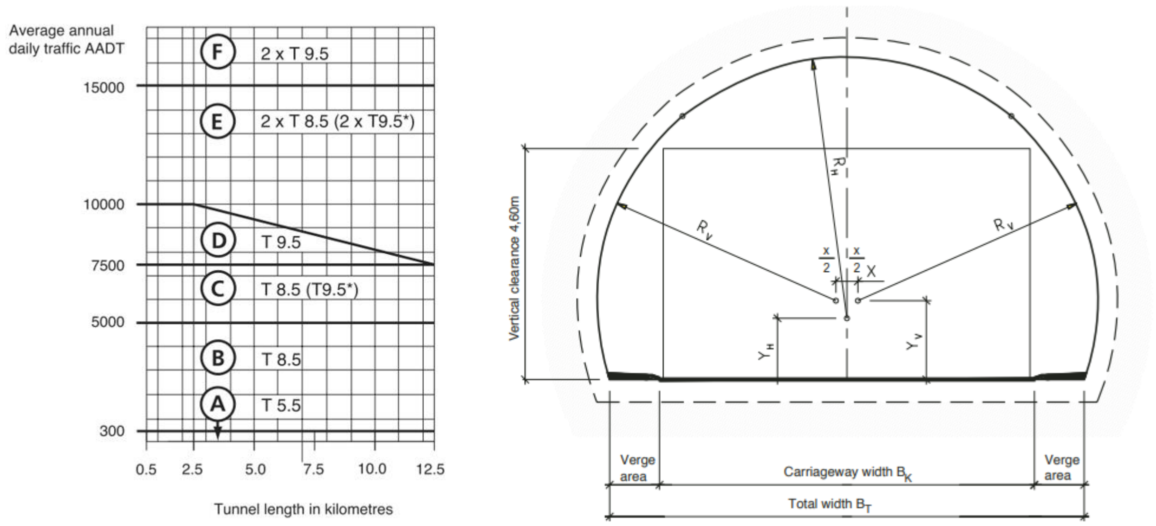


Figure 2. *Rock class distribution over tunnel alignment*

5. TUNNEL SHAPE, SIZE, AND EXCAVATION METHOD

Road tunnels serve as an alternative transportation system to a surface road or bridge, offering reduced travel time and distance, and should have the same traffic capacity as the surface roads they are intended to replace. The shape and dimensions of the tunnel cross-section are primarily determined by serviceability requirements, prevailing ground conditions, and tunnel construction aspects (Ezekiel, 2018). Since the construction is considered to follow the drill and blast or sequential excavation method, a horseshoe-shaped tunnel has been proposed. Traffic volume, being a key factor in road design (number of lanes and road width), is normally assessed using Annual Average Daily Traffic (AADT). According to the Highway Management Information System (HMIS) unit, Department of Roads, Ministry of Physical Infrastructure and Transport, Government of Nepal, the recorded AADT on the Pokhara – Baglung Highway is 9157 in PCUs in 2024/2025. Based on these traffic trends, projected growth, and the planned connection of the Baglung-Pokhara Highway to the Kaligandaki Corridor, the Annual Average Daily Traffic (AADT) is estimated to cross over 10,000 vehicles in the coming years. Since section 17.3 (Road tunnels) of the 'Nepal Road Standard 2070' does not provide details of the road tunnel geometry, the Norwegian Standard has been adopted as the reference for defining the detailed geometrical cross-section of the planned road tunnel. Hence, the tunnel cross-section profile selected for this 14 km long road tunnel is type 9.5 (T9.5), following Norwegian Public Roads Administration (2004) as illustrated in Figure 3 and Table 2.



(a) (b)

Figure 3. *(a) Traffic pattern (b) Cross-sectional geometry of tunnel (Norwegian Public Roads Administration, 2004)*

The tunnel system includes all underground structures such as cross passages, adits, shafts, escape routes, and other ancillary components such as ventilation shafts for technical equipment. These elements will be designed based on operational, organizational, and safety considerations. According to DOR (2013), the tunnel will have a maximum gradient of less than 7%. The selection of a tunnel excavation depends on factors such as the type of ground, tunnel size, the availability of resources, including machinery/equipment, funds, and time. The conventional drill and blast method of tunneling could be well-suited for the construction of this road tunnel. The detailed dimensions of the proposed tunnel profile have been presented in Table 2.

Table 2. *The cross-section geometry (profile) details of the road tunnel*

Description	Details
Length	14 km
Total Effective Width (B_T)	9.5 m
Carriageway Width (B_K)	7 m
Theoretical Excavation Area	66.53 m^2
Theoretical Required Area	53.53 m^2
Roof Radius (R_H)	5.2 m
Wall Radius (R_V)	4.79 m
Centre Distance to Roof Radius(Y_H)	1.22 m
Centre Distance to Wall Radius(Y_V)	1.57 m
Centre Point to Wall Radius(X)	0.44 m
Shape	Horseshoe shape
Construction Method	Drill and blast
Strike of Tunnel	N 75° E

6. ESTIMATION OF ROCK MASS PROPERTIES

For analyzing the stability of the tunnel, it is crucial to understand the rock mass characteristics and their interaction with the provided support under loading conditions. Proper estimation of the physical and mechanical properties of the rock mass is essential for understanding the behavior of the surrounding rock mass. Table 3 summarizes the rock mass properties along the tunnel alignment. The physical and mechanical characteristics of intact rocks were obtained either by field mapping or laboratory tests conducted by Panthi (2006) and Shrestha and Panthi (2014).

Table 3. *Engineering geological, and mechanical properties of rocks at different chainages*

Description/Chainage(m)	0+285	5+000	7+300	9+820	13+220
Rock type	Graphitic phyllite	Siliceous phyllite	Meta sandstone	Siliceous phyllite	Quartzite
Uniaxial compressive Strength (UCS), MPa	39	39	73	39	221
Young's modulus (E), GPa	27	14	46	14	83
Poisson's ratio(ϑ)	0.1	0.1	0.14	0.1	0.2
Unit weight (γ), MN/m^3	0.0278	0.0286	0.0265	0.0286	0.026
GSI	48	26	60	48	55
Vertical stress (σ_v), MPa	3.48	12.36	26.29	14.24	9.54
Friction angle(ϕ)	43^0	39^0	47^0	39^0	55^0
Cohesion (C) MPa	1.52	0.9	4.2	0.9	12.6

7. STABILITY ANALYSIS METHODOLOGY

Stability assessment is a prime task for planning excavation and construction strategies and estimating rock support. The stability of tunnels primarily depends on two factors: rock mass quality (strength of rock mass, deformability properties, strength anisotropy, conditions of discontinuities, and degree of weathering) and mechanical processes (groundwater conditions and influence of in-situ stress) (Panthi, 2023). Various methods are in practice to assess the stability of the tunnel based on these factors. In this paper, stability conditions were assessed through both analytical and numerical approaches across various sections, as illustrated in Figure 2, characterized by differing rock mass qualities and rock cover conditions.

7.1. Analytical/ semi-analytical approaches

When the strength of the rock mass is lower than the induced stress, overstressing can occur around the periphery of the underground opening. Instability, such as rock spalling and rock bursts, is typically observed in relatively unjointed and massive rock masses. In contrast, squeezing-related instabilities are characteristic of low-quality, highly deformable rock mass (Palmström, 1995). In addition, underground structures at shallow depths with jointed rock mass experience low gravity stresses within the surrounding rock mass, which result in increased stress anisotropy. Rocks are often highly weathered near the surface, which reduces interlocking between the rock blocks (the natural arching effect) and increases the risk of wedge falls (block falls). Potential wedges can be identified with structural, geometrical, and geological data (Hoek, 2001).

Before conducting the analytical and numerical analyses, the squeezing conditions in the selected sections were initially evaluated using empirical criteria proposed by Singh et al. (1992). Although this approach is useful for identifying the occurrence of squeezing, it does not provide a quantitative measure of its severity. In sections classified as non-squeezing, where the rock mass exhibited a distinctly jointed structure, wedge stability analysis was employed to assess potential block failures. At both portal sides of the tunnel, the rock mass is intersected by multiple joint sets, resulting in the formation of wedges that may slide or fall into the tunnel opening. Hence, to investigate these potential modes of instability within the jointed rock mass, the UNWEDGE software was used.

Analytical and semi-analytical approaches serve as valuable tools in assessing tunnel stability, particularly during planning and design phases. These methods provide insight into stress redistribution, deformation patterns, and potential failure mechanisms surrounding tunnel openings. In sections with squeezing ground conditions, the stability analysis was conducted using an analytical Convergent Confinement Method (CCM), which simplifies the 3D rock support interaction into a more practical 2D analysis by integrating Ground Reaction Curve (GRC), Support Characteristic Curve (SCC), and Longitudinal Deformation Profile (LDP). This approach provides a realistic representation of rock mass convergence as confinement decreases around the tunnel, and the results were subsequently verified through numerical modeling to ensure their reliability.

7.2. Numerical Modeling

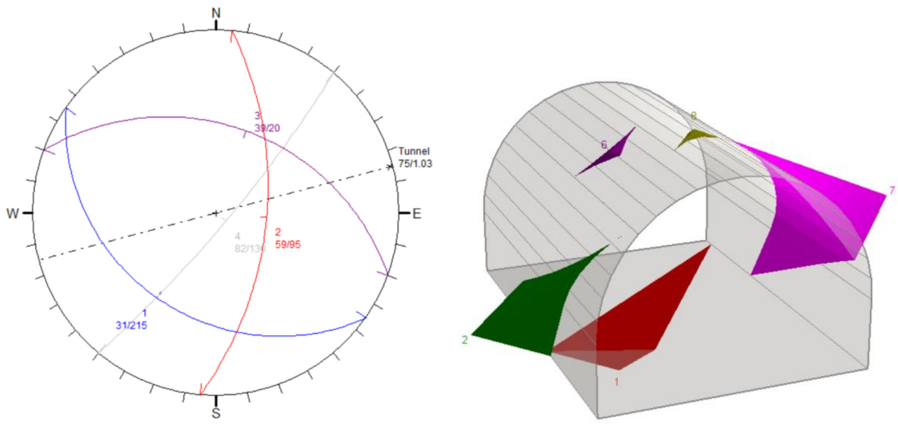
For the present study, wedge analysis was conducted using the UNWEDGE program of Rocscience to identify the potential wedge. The mapped dip direction and dip amount of major discontinuities have been utilized to identify potential wedges that can slip from walls or fall from the roof, and the safety factors of these wedges have been determined. For wedge stability, rock bolts and shotcrete can be installed, depending on the size, shape, and type of wedges (Hoek, 2001).

Numerical simulations of tunnel excavation have been conducted for various sections (Figure 2) with rock masses of varying quality conditions and overburden depths. A two-dimensional finite element software (RS^2) is used to develop numerical models. The tunnel excavation sequence is simulated by assuming a full-face excavation method. The external boundary of the model domain is defined as five times the diameter of the tunnel to minimize the influence of boundary effects. All boundaries of the box models are subjected to fixed constraints. Mohr and Coulomb failure criterion is used to characterize the elastoplastic behavior of the surrounding rock mass. The simulations have been conducted for a horseshoe-shaped tunnel with a span of 11.35 meters. A graded mesh composed of six-noded triangular elements is generated to ensure sufficient resolution for the tunnel boundary.

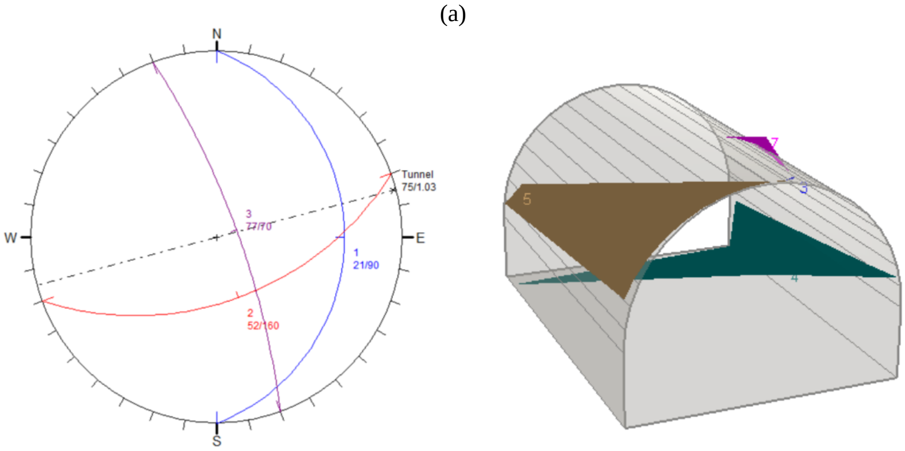
The model accounts for both vertical and horizontal stresses resulting from the gravitational effect. In addition, tectonic stresses significantly contribute to the overall magnitude of horizontal stress. In the central region of the Himalayas, tectonic stresses are predominantly oriented in the north-south direction (Panthi, 2012). As the tunnel alignment follows a 75^0-255^0, orientation, it experiences substantial in-plane tectonic stress (normal to the tunnel alignment). Further, the field observation and assessment concluded that the rock mass at the weakness zone (section 5+000m) will represent weathering grade II, which subsequently will reduce the intact rock strength and elasticity modulus by 40% (Panthi 2006), giving intact rock strength and elasticity modulus of 25 MPa and 10 GPa, respectively. Hence, the rock mass strength and rock mass deformation modulus given in Table 1 have been reduced accordingly to the analysis.

8. RESULTS

The trend of the tunnel axis is 75^0 clockwise from the North, and it plunges at 1.03^0 from the eastern portal, respectively. While analyzing the wedge, the computer program UNWEDGE identified various locations and dimensions of potential wedges, along with safety factors, that formed in the roof and side walls of the tunnel opening. At section 0+285m, where four joint sets were mapped. A total of eight wedges have been formed around the tunnel opening with a different factor of safety, where the roof wedge [8] is found to be unstable (Figure 4a). Similarly, three joint sets were mapped at section 13+220m, where a total of seven wedges may form around the opening of the tunnel. Most of these wedges were found to be stable (Figure 4b).



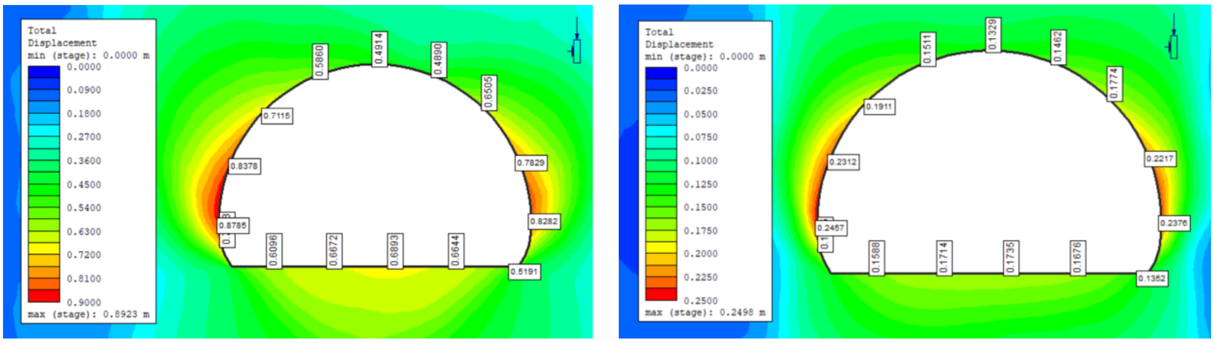
(a)



(b)

Figure 4. *Stereographic projection and 3D wedge view (a) at section 0+285m (b) at section 13+220m*

Tunnel excavation results in a reduction of the strength of the surrounding rock mass, which induces plastic deformation (squeezing). This effect is particularly pronounced in fracture zones that are already in a plastic state prior to excavation. This is further evidenced by the significant deformations observed along the tunnel periphery. The analysis presented in this section revealed that a maximum strain of 13.63% is determined using the Convergence Confinement Method and 15.01% by numerical analysis conducted before the installation of tunnel support systems (Figure 5).



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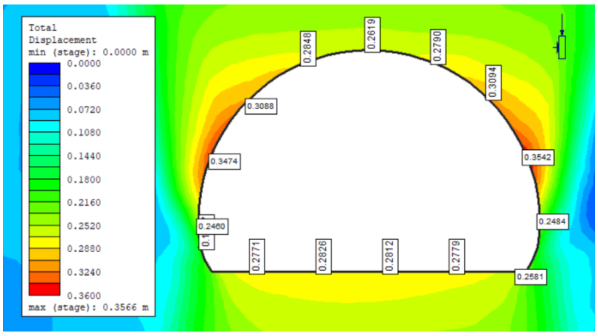
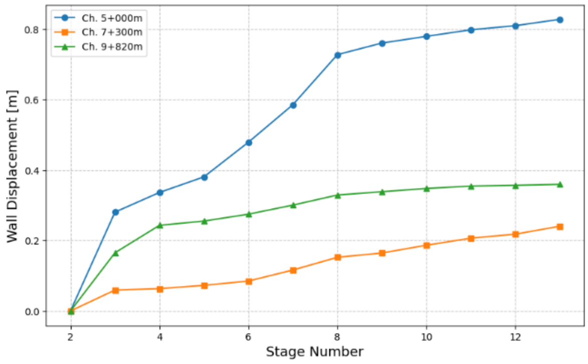


(c)



(d)

Figure 5. *Deformation around the tunnel periphery (a) at section 5+000m (b) at section 7+300m (c) at section 9+820m, and (d) Horizontal wall displacement along the sections*

At sections 7+300m and 9+820m, the calculated tunnel strains using the Convergence Confinement Method are 0.24% and 3.75 %, respectively, while the corresponding values obtained from numerical modeling are 0.32% and 6.6%, respectively. As illustrated in Figure 5(d), the maximum deformation occurs along the tunnel wall at chainages 5+000m and 9+820m, whereas 0.32% of deformation occurs at the tunnel invert in section 7+000m, indicating slight floor heaving.

9. DISCUSSION

The stability assessment and deformation analysis of the tunnel have revealed critical insights into the rock mass behavior and strategies for planning support systems. Both the western and eastern portals are situated on a gentle slope, where the rock mass comprises quartzite and phyllite rocks with intercalation of metasandstone, exhibiting three or more joint sets on each side. Construction of the portal requires cutting the gentle slope to some extent. Cut slopes shall be stabilized permanently by shotcrete and rock bolts or other slope protection measures. The wedge stability analysis conducted by UNWEDGE software identified several potential wedges at sections 0+285m (Northeastern portal) and 13+220m (Southwestern portal). The stereographic projection and 3D wedge model, as depicted in Figure 4, revealed the formation of distinct wedges around the tunnel perimeter. These wedges are stable in massive quartzite; however, one roof wedge in section 0+285m is found to be unstable, indicating the need for support in the roof where instability is most pronounced.

The tunnel site is characterized by numerous shear zones, faults, and folds. The stress redistribution in folded, faulted, and fractured rock mass due to the excavation reduces the rock mass strength and contributes to further instability, causing squeezing conditions. Field observations and the deformation analyses exhibit these concerns, particularly at the fracture zones at 5+000m, where the presence of crushed metasandstone and phyllite resulted highest tunnel strain. This result indicates the need for reliable support measures with yielding joints. In contrast, section 7+000m, where fair quality rock mass (metasandstone) and high rock cover prevail, showed minimal deformation, whereas section 9+820m, which is characterized by weathered siliceous phyllite, showed moderate strain levels.

The quality of the rock mass, along with the proposed tunnel alignment, exhibits substantial spatial variation over short distances. This heterogeneity is primarily attributed to active tectonic processes, intense monsoons, and the presence of geological structural features. Such variations in geological conditions pose substantial engineering challenges, as evidenced by the evaluation results obtained for selected specific sections of tunnel alignment. These findings indicate the necessity for section-specific support designs and the implementation of continuous monitoring strategies throughout the construction period.

In some cases, the extent and reliability of subsurface investigations are compromised due to logistical, financial, or topographical constraints, particularly in regions with steep terrain, where conventional investigation methods may not yield accurate or comprehensive data (KC et al., 2022). Therefore, the application of advanced and reliable subsurface investigation techniques is essential to ensure the safe and effective execution of tunneling works.

Beyond the technical considerations, the tunnel project holds considerable socioeconomic and environmental significance. This road tunnel is expected to reduce travel time and transportation costs, thereby promoting local and regional trade, which will significantly boost the economy and tourism in the region. Overall, the integration of analytical and numerical analysis has enabled the development of reliable support measures tailored to the prevailing rock mass conditions. These engineering solutions, coupled with socio-economic evaluations, highlight the tunnel's transformative potential for remote mountain communities and regional trade.

10. CONCLUSIONS

This paper provides an understanding of the stability and deformation analysis of the proposed road tunnel in the Lesser Himalayas, offering valuable insights into the rock engineering behavior of the surrounding rock mass. The UNWEDGE program identified the potential wedges at the sections (0+285m and 13+220m), with various safety factors, emphasizing the potential for instability, especially around the roof and sidewalls. Strain analysis using the Convergence Confinement Method and numerical method indicates substantial plastic deformation, particularly in the weakness zone, with strain observed at 5+000m (up to 15.01%). In contrast, sections like 7+300m showed lower deformation due to stronger rock mass. These findings underline the necessity for section-specific support measures, particularly in fracture zones affected by faulting, folding, and jointing. Beyond technical considerations, the tunnel project presents considerable economic, social, and ecological benefits, improving regional connectivity. Overall, the project development integrating efficient engineering geological measures followed by optimized community benefits could demonstrate the tunnel's transformative role in improving infrastructure resilience and regional development in the challenging Himalayan terrain.

11. ACKNOWLEDGMENTS

The authors would like to acknowledge NORAD, which supported this research through NORHED II Project 70141 6: *Capacity Building in Higher Education within Rock and Tunnel Engineering in Nepal*, operated by the Norwegian University of Science and Technology (NTNU), Norway, in collaboration with Pashchimanchal Campus, Institute of Engineering (IoE-WRC), Tribhuvan University (TU), Nepal. The authors are thankful for both financial and moral support in conducting this research.

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