Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Alignment Selection for Hydro Tunnels: A Case Study of Headrace Tunnel of Lower Balephi Hydropower Project, 20 MW

Kapil Raj Adhikari [a], Chhatra Bahadur Basnet [b], Ghan Bahadur Shrestha [c]

[a, b, c] *Pashchimanchal Campus, IOE, Tribhuvan University, Nepal*
[a] kapiladhikari2047@gmail.com, [b] chhatra.basnet@gmail.com, [c] gb.shrestha20@gmail.com

Abstract
The proposed Headrace Tunnel of the Lower Balephi Hydropower Project lies in the Lesser Himalayan region in Sindhupalchowk, Nepal. This paper discusses the key factors that influence the selection of the tunnel alignment for the hydro tunnel, including joint rosette, and an engineering geological map prepared using rock mass data collected along the Balephi-Jalbire road section from Phalamye Sanghu to Balautye. The major rock types present in the study are phyllite, Metasandstone, Schist, and Gneiss. The study also focuses on mapping the rock mass along the proposed tunnel alignment, utilizing three major rock classifications: Rock Mass Quality (Q), Rock Mass Rating (RMR), and Geological Strength Index (GSI). The findings derived from this study possess the potential for equal applicability to other hydro tunnel projects.

Keywords
Lower Balephi Hydropower Project, RMR, Q, GSI, Tunnel Alignment.

1. Introduction

In the context of hydropower development in Nepal, the challenging terrain, characterized by rugged topography and steeply flowing rivers, offers a significant advantage in terms of high head potential [1]. To fully capitalize on this potential without compromising efficiency, the most practical approach for water conveyance often involves the use of tunnels rather than traditional canal systems. However, the geological characteristics of the region play a pivotal role in determining the feasibility and design of underground structures, particularly tunnels.

Nepal has young mountains and fragile geology and has undergone the effect of tectonic movement resulting in highly folded, faulted, and shearing of rock mass [2]. This, in turn, will affect the underground structure as a challenging task forming the highly sheared, schistose, and an-isotropic rock mass [3]. Tunneling is considered an art, necessitating a diverse range of skills and expertise at varying levels. It involves strategic planning and decision-making, as well as essential non-geological aspects, throughout the planning, pre-feasibility, and construction stages of tunneling projects. Consequently, analyzing rock mass properties, topographical features, and geological conditions plays a crucial role in determining the appropriate placement and selection of the optimal alignment route. This choice, in turn, significantly impacts the overall stability and vitality of the tunnel, influencing both its economic and structural aspects[3].

The Lesser Himalayan region primarily comprises weak rock masses, including non-fossiliferous sedimentary and metasedimentary rocks like phyllite, schist, quartzite, limestone, dolomite, and occasional granitic intrusions. Tunneling in this area presents unique challenges, necessitating the use of suitable tunneling techniques and technologies. Comprehensive geological investigations and surveys are crucial for understanding ground conditions and potential hazards.

2. Balephi Hydropower Project

The proposed Lower Balephi Hydropower Project, with an installed capacity of 20MW, is a run-of-river (ROR) type project located in the Sindhupalchowk district of Bagmati Province in central Nepal, as shown in Figure 1.

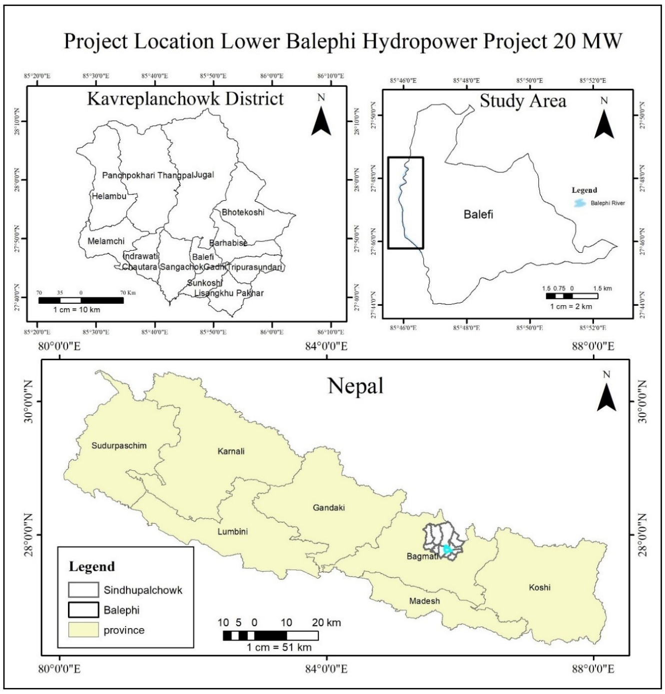

Figure 1: Project Location

The project has a design discharge of (Q %40), 30.60 m3/s, and a gross head of 75.50m. The project components include an Intake, a Headrace Tunnel of length 5145.50 m of inverted D of 5m×5m, a penstock tunnel, the Surface powerhouse, and a Tailrace. Construction work on the project is yet to commence under Sajha Power Development.

3. Geology of the project area

The project area is located within the Lesser Himalayan Zone of Central Nepal shown in Figure 1. Geologically the Lower Balephi Hydroelectric Project lies entirely within the Kunchha formation of the Lower Nawakot group of the Nawakot complex . The lower part of the Kuncha Formation consists of the alteration of phyllite, phyllitic quartzite, and phyllite [4] . In addition, the area consists of Quaternary deposits of Balephi Khola along its bank. The riverbeds and flood plains are found full of recent gravel and sand.

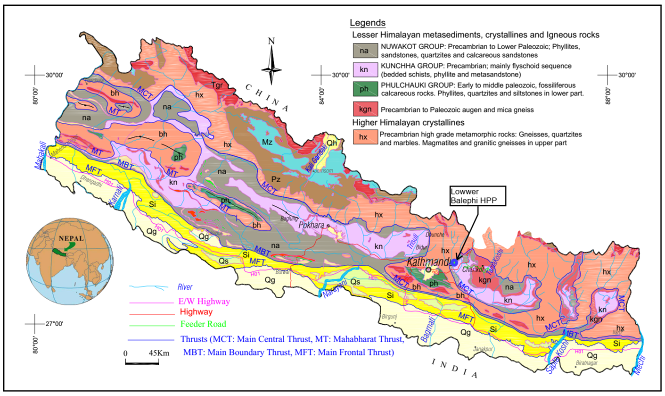

Figure 2: Geological Map of Nepal [5]

Balephi Khola river terraces and rock outcrops can be found in the project area. The rock outcrop regions have moderate to steep slopes. The major types of rock found in these locations are phyllite, metasandstone, gneiss, and schist.

Table 1: Stratigraphy of the Project Area l

Complex	Group	Formation	Main Lithology	Geological Age
Mahabharat Thrust (southward extension of the MCT)				
Nuwakot	Upper Nuwakot	Robang Formation	Phyllite, Quartzite	Early Paleozoic
		Malekhu Limestone	Limestone, Dol omite	Precambrian
		Benighat Slates	Slate, Argillites	Precambrian
	Lower Nuwakot	Dhading Dolomite	Stromatolitic Dolomite	Precambrian
		Nourpul Formation	Phyllite, Metasandstone	Precambrian
		Dandagaon Phyllite	Phyllite	Precambrian
		Fagfog Quartzite	White Quartzite	Precambrian
		Kuncha Formation	Phyllite, Quartzite	Precambrian

Foliated phyllite and phyllitic quartzites (metasandstones) are interbedded throughout the project area and are characterized by medium to very thick bedding, wavy features, and mild to moderate weathering. The exposed rocks, which are randomly folded and discontinuous, contain quartz veins. Phyllite dominates the northern portion, extending from the headwork to Naubise Khola, while phyllite quartzite is prevalent in the southern part of the project area. In general, the rocks exhibit a dipping orientation, with dip angles ranging from 30 to 60 degrees towards the northeast.

4. Field Assessment and Data Collection

Surface mapping is conducted at 31 distinct locations along the Balephi-Jalbire road section, focusing on exposed outcrops. This assessment involves gathering critical data, including the Rock Mass Rating (RMR), Q-value, Geological Strength Index (GSI), and the identification of rock types present at these sites are phyllite, Metasanstone, Schist, and Gneiss.

4.1 Rock Mass Classification

During the initial project phases with limited information available about the rock mass, employing a rock mass classification system proves highly advantageous. Empirical methods, with a primary focus on RMR, Q, and GSI, are commonly utilized in the pre-feasibility and feasibility design phases of tunneling and underground construction projects. These systems systematically evaluate geological and geotechnical rock parameters, including strength, jointing, weathering, and groundwater conditions. This assessment assists in predicting the behavior of the rock mass during excavation and guides the selection of suitable support systems.

4.1.1 Rock Mass Rating (RMR)

The Rock Mass Rating (RMR) system, conceived by Z.T. Bieniawski in 1973, remains a widely adopted classification method in geomechanics. It systematically assesses rock masses based on six key parameters: intact rock strength (point load or uniaxial compressive strength), rock quality designation (RQD), discontinuity spacing, discontinuity condition, groundwater influence, and discontinuity orientation. Assigning numerical values to these parameters yields an RMR value between 0 and 100. This value plays a pivotal role in designing support systems for mining and tunneling, offering a comprehensive evaluation of rock mass quality and behavior.

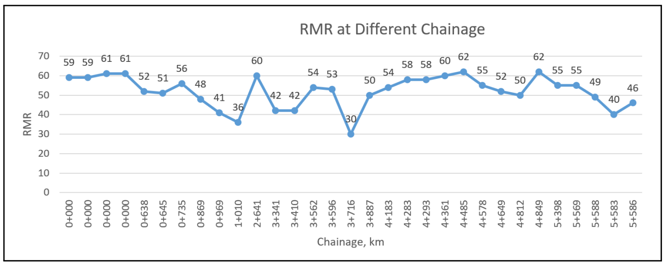

Figure 3: RMR of rock mass along the chainage

Discrepancies in assessing RMR values across various rock types are influenced by factors like discontinuity spacing, groundwater presence, discontinuity state, roughness, and infillings. These factors are graphically illustrated in Figure 3, with values ranging from 30 to 62. The accompanying doughnut chart in Figure 4 shows that the region predominantly consists of Class III rock types 77%, with Class IV 10%, and Class II 13%.

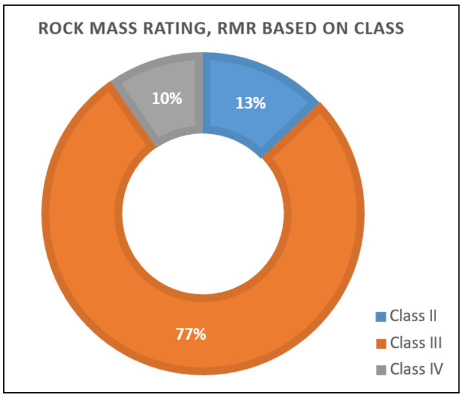

Figure 4: Doughnut RMR at different locations

4.1.2 Geological Strength Index (GSI)

The Geological Strength Index (GSI), introduced by Evert Hoek in 1994, assesses the strength and deformation characteristics of rock masses for rock engineering.To determine the GSI value in the field, we use a classification chart for heterogeneous rock masses provided by Marinos and Hoek (2000). It relies on visual inspection of geological factors, including rock type, structure, weathering, and alteration. Engineers use GSI to understand rock mass strength and deformation, guiding support system selection and excavation design for safety and stability. It currently measures the Geological Strength Index for jointed rock masses. In the field, at 31 different locations, the GSI value is estimated, and a graphical representation is displayed in Figure 5, with a minimum average value of 30 and a maximum value of 65 at different locations.

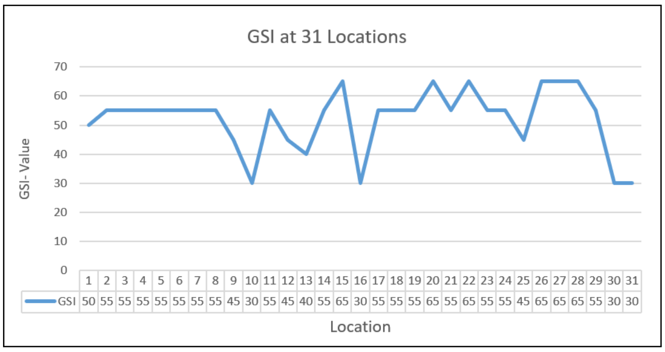

Figure 5: Representation of GSI at Different Locations

4.1.3 Rock mass quality (Q value)

The Q system of rock mass classification was developed at the Norwegian Geotechnical Institute (NGI) by Barton et al. in 1974. Since then, there have been two major updates in 1993 and 2002, incorporating underground structures basically, tunnel and cavern data from Norway, Switzerland, and India. The Q-method is also employed in pre-investigations, and Construction for tunnels, caverns, and rock mechanical calculations [6]. When planning underground projects, it's crucial to provide detailed rock mass descriptions to achieve optimal design and obtain reliable predictions for rock support and cost estimates. The Q value varies on a logarithmic scale from 0.001 to a maximum of 1,000, and it is defined by six key parameters: Rock Quality Designation (RQD), Number of joints (Jn), Roughness of the most unfavorable joint (Jr), Degree of alteration (Ja), Water inflow (Jw), and Stress reduction factor (SRF). The Q-system utilizes a support chart to estimate the amount of support required based on the Q-value and the height or span of the underground opening as shown in Figure 6.

$$Q = \frac{RQD}{Jn} \cdot \frac{Jr}{Ja} \cdot \frac{Jw}{SRF}$$

In conjunction with the RMR and GSI systems, the Q system of classification is utilized in the field to enhance the assessment of rock parameters.The criteria RQD, joint number, joint alteration, joint set number, joint alternation number, joint roughness, and joint reduction factor all play a role in the Q-system of rock mass classification along the 31 locations. Based on the field assessment data along the chainage, a graphical plot of Q-values, ranging from a minimum of 0.99 to a maximum of 5.67, is presented in Figure 7. The higher the Q-value, the better the quality of the rock mass, and the less support is generally required for excavations. According to the pie chart in Figure 8 of Doughnut shape, the majority of the rock mass is classified as 'Fair' (Class C), accounting for 77%, while only 10% of the rock mass is categorized as 'Poor' (Class D), with 13% falling into the 'Good' category (Class B).

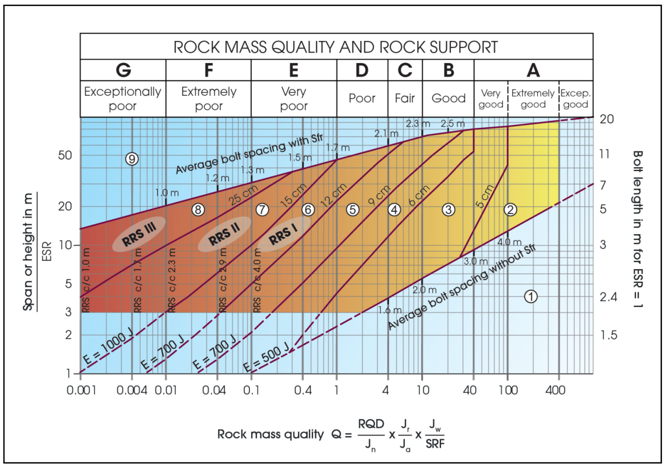

Figure 6: Permanent support recommendations based on Q-values and span/ESR (NGI, 2015)

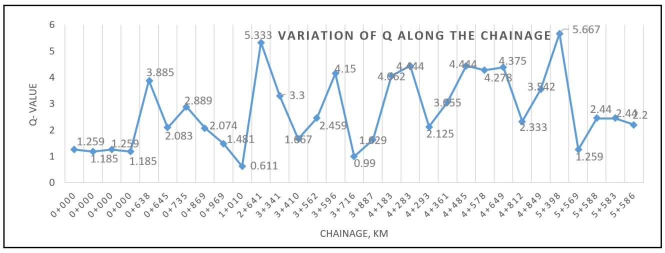

Figure 7: Q-value along the chainage

The surface mapping is conducted at 31 distinct locations along the Balephi-Jalbire road section on exposed outcrops. Table 2 provides information on RMR, Q-values, GSI values, and the corresponding rock types in these locations.

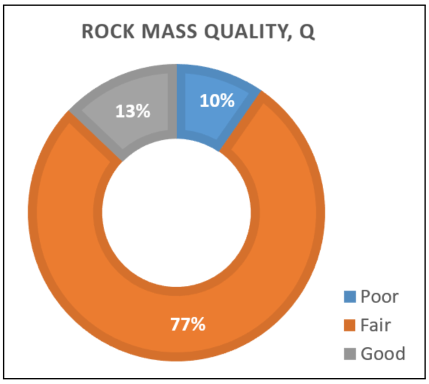

Figure 8: Pie chart (Doughnut) Q-Value at different locations

Table 2: Rock Mass Classification along the 31 locations

Chainage (km)	RMR	Q	GSI	Rock Type
0+000	59	1.259	45-60	Metasandstone
0+000	59	1.185	45-65	Metasandstone
0+000	61	1.259	45-65	Metasandstone
0+000	61	1.185	45-65	Metasandstone
0+638	52	3.885	45-65	Phyllite
0+645	51	2.083	45-65	Phyllite
0+735	56	2.889	45-65	Phyllite
0+869	48	2.074	45-65	Phyllite
0+969	41	1.481	35-55	Phyllite
1+010	36	0.611	30-45	Phyllite
2+641	60	5.333	45-65	Phyllite
3+341	42	3.3	35-55	Phyllite
3+410	42	1.667	35-50	Phyllite
3+562	54	2.459	45-65	Phyllite
3+596	53	4.15	55-75	Metasandstone
3+716	30	0.99	30-45	Phyllite
3+887	50	1.629	45-65	Phyllite
4+183	54	4.062	45-65	Phyllite
4+283	58	4.444	45-65	Schist
4+293	58	2.125	55-75	Gneiss
4+361	60	3.055	45-65	Schist
4+485	62	4.444	55-75	Schist
4+578	55	4.278	45-65	Schist
4+649	52	4.375	45-65	Schist
4+812	50	2.333	35-55	Schist
4+849	62	3.542	55-75	Schist
5+398	55	5.667	55-75	Schist
5+569	55	1.259	55-75	Schist
5+588	49	2.44	45-65	Metasandstone
5+583	40	2.44	30-45	Metasandstone
5+586	46	2.2	30-45	Phyllite

5. Tunnel Orientation

The selection of location and orientation for underground structures depends on the characteristics of the rock mass's joint and discontinuity systems in the area. In shallow to moderately overburdened tunnels, aligning with the bisector of the larger joint angle is appropriate. However, in high-stress environments, it's advisable to follow the orientation of the major principal stress for improved stability and safety. For openings at shallower or intermediate depths, a fundamental guideline is to orient the length axis along the bisection line of the maximum intersection angle between the two dominant joint directions, including bedding or foliation partings [7]. This approach ensures the structural integrity of underground constructions.

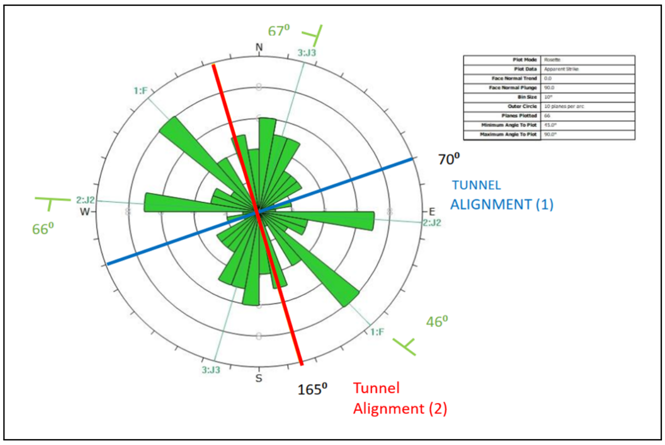

Figure 9: Joint rosette showing the orientation of the main joint sets and tunnel alignments

In the field , extensive mapping efforts focus on identifying major discontinuity systems, which include features such as bedding or foliation planes, cross joints, and significant fault or weakness zones within the area. These discontinuities are carefully assessed for their orientations, providing critical data for determining the optimal tunnel alignment. Based on the field data being collected at 31 locations, as depicted in Figure 9, the tunnel is favorably aligned with respect to the foliation joints (F). However, it is running parallel to the random joints, which may pose instability issues for the tunnel alignment. On the other hand, tunnel alignment (2) with a trend of 165°, which is nearly perpendicular to the foliation joint set, represents the most favorable alignment, and alternate tunnel alignment (1) with a trend of 70°. The rock mass and the rosette diagram indicate the dominance of three joint sets and random joints, as shown in Figure 9.

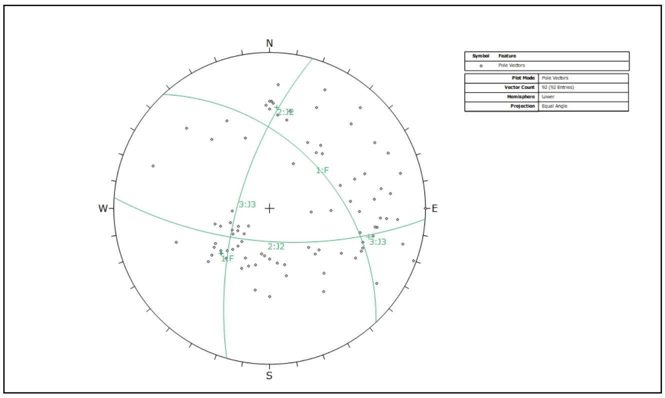

Figure 10: Plot of the Foliation, Joint set1 and Joint set2

6. Engineering Geological Map

Engineering geological map offers detailed information about bedrock and soils, emphasizing the physical and mechanical properties of the rock mass. It assists engineers and geologists in evaluating sites for construction, including buildings, roads, slopes, and tunnels. This map covers rock types, soil composition, groundwater levels, slope stability, and geotechnical properties. Engineering geological maps are created by combining field observations, geological mapping, and laboratory testing of rock samples.

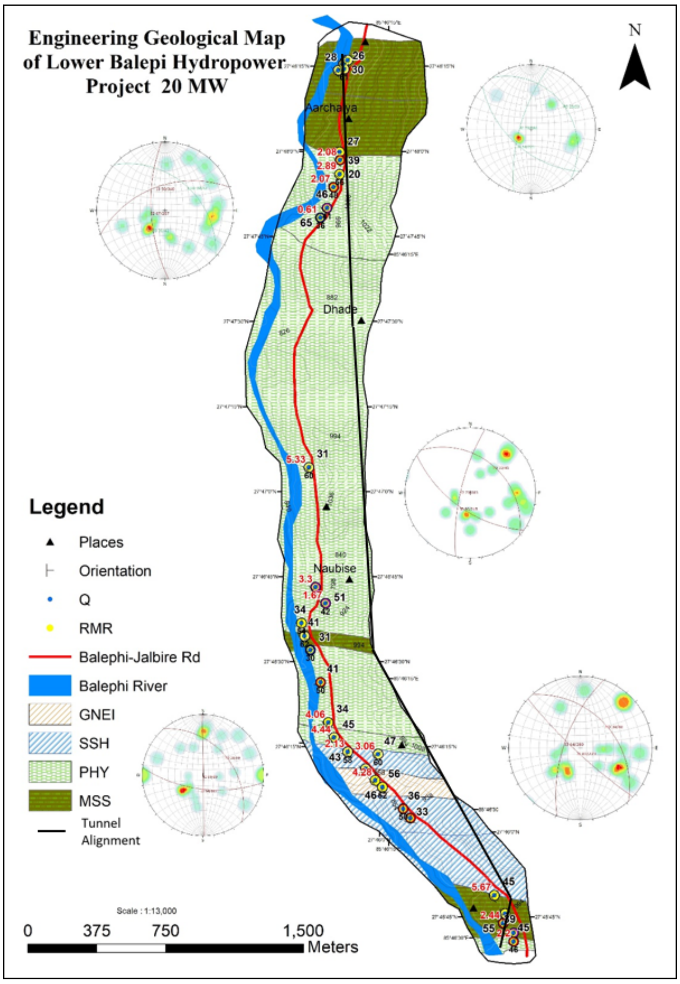

Figure 11: Engineering geological map of the Lower Balephi Hydropower Project

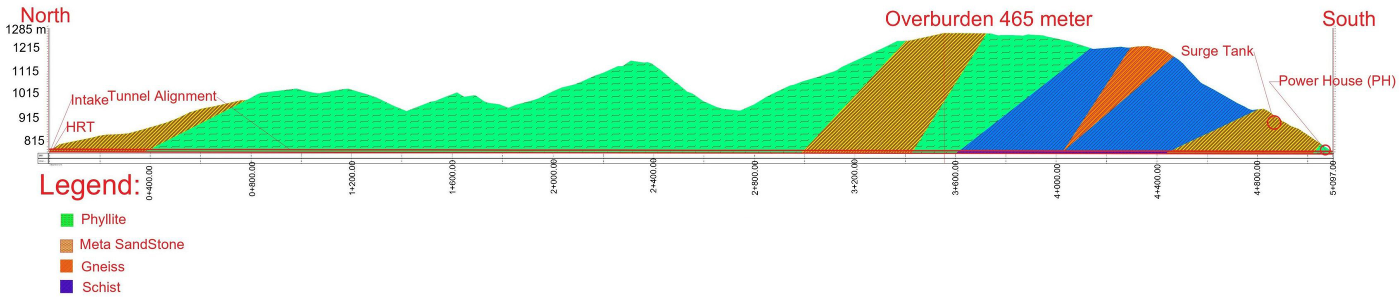

Figure 12: Geological profile of Lower Balephi Hydropower project

Field data, including orientation (dip amount and strike) and rock types, collected at 31 locations, were integrated into a georeferenced topographical map obtained from the survey department at a 1:10,000 scale, using ArcGIS. The location's contour was overlaid onto a Digital Elevation Map. Stereographic projection maps, created with the assistance of Rocscience Dips v6.00, were then incorporated into the engineering geological map. These maps provide crucial information for assessing the suitability of the alignment for the 20MW, Lower Balephi hydropower project's headrace tunnel shown in Figure 10. Also, a longitudinal geological profile of the project site is shown in Figure 11. This comprehensive approach, combining field data, advanced mapping tools, and geological profiles, facilitates the selection of the tunnel alignment for the Lower Balephi hydropower project.

7. Result

The study was done at 31 locations starting from Phalamye Sangu with a chainage of 0+000 to Balautye 5+586 km lies in the lesser Himalayan zone with dominant rock type of, phyllite, metasandstone, Schist, and Gneiss, With the presence of three and random joint sets. The majority of rock mass at the different locations indicated that the rock mass predominantly fell into Class III, as classified by the Rock Mass Rating (RMR) system. Simultaneously, it was categorized as "fair" according to both the Q-system. The average Geological Strength Index (GSI) values ranged from 30 to 65, showcasing a spectrum of moderate to good rock quality. The analysis of joint rosette data has revealed that the most favorable alignment for the project is represented by alignment (2) with option tunnel alignment (1), characterized by a trend of 165°, as depicted in Figure 9. Additionally, an engineering geological map and a geological profile have been meticulously generated, incorporating the engineering geological parameters collected along the section.

8. Conclusion

Surface mapping along the road section alignment at 31 distinct locations revealed that the prevailing rock mass was primarily categorized as Class III according to the RMR system in Figure 4, while the Q-system assessment indicated a fair rating as shown in Figure 8. This classification proved advantageous for tunnel planning, as evidenced by its thoughtful incorporation into the Engineering Geological Map as shown in Figure 11. However, it is important to note that these classifications are not a guarantee of the exact underground conditions, and additional investigations may be necessary to fully assess the rock mass properties and potential hazards. Overall, this information is a good indicator for selecting a suitable alignment for the tunnel, but further assessments and evaluations should be conducted before construction.

9. Recommendation

The significance of engineering geological assessment in achieving optimal tunnel design is paramount and should always be upheld. This study primarily adopted an empirical approach, heavily reliant on visual inspections of the rock mass using Rock Mass Rating (RMR), Quality Index (Q), and Geological Strength Index (GSI) charts. Unfortunately, the mechanical properties of the rock mass were not assessed due to the absence of laboratory testing. Additionally, the study was limited by a selective choice of locations on exposed outcrops. A more extensive study consisting of fault zones and topography should be undertaken for the selection of critical locations, with a focus on subsurface conditions, which would have rendered the study more comprehensive

Acknowledgments

The authors express their sincere gratitude to Sajha Power Development Pvt. Ltd. for providing generous permission that facilitated the successful completion of the field assessment and greatly contributed to the accomplishment of the study.

References

[1] Basel Ismail. *Renewable Hydropower Technologiesl*. InTechOpenl, 2017.

[2] B. N. Upreti. An overview of the stratigraphy and tectonics of the nepal himalaya. *Journal of Asian Earth Sciences*, 17:577–606, 1999.

[3] K. Panthi. *Analysis of Engineering Geological Uncertainties Related to Tunnelling in Himalayan Rock Mass Conditions*, volume 5. 2006.

[4] J. Stöcklin and K. D. Bhattarai. Geology of the kathmandu area and central mahabharat range, nepal himalaya. 1977. Report of Department of Mines and Geology/UNDP, 86p.

[5] K. Panthi and C. Basnet. Design review of the headrace system for the upper tamakoshi project, nepal. *International Journal on Hydropower and Dams*, 24, 2017.

[6] NGI2015. *Using the Q-System Rock Mass Classification and Support Design*.

[7] B. Nilsen and A. Thidemann. *Rock Engineeringl*. Norwegian Institute of Technology (NTH), Division of Hydraulic Engineeringl, 1993.