eISSN: 2976-1190

Journal of Engineering and Sciences

Vol. 2 Issue 1 November 30, 2023

Journal homepage: **Journal of Engineering and Sciences (nepjol.info)**

Publisher: Research Management Cell, Pashchimanchal Campus, Lamachour, Pokhara

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Evaluation and stability assessment of road cut slope at Bhalupahad of Syangja District along Siddhartha Highway; Western Nepal

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(Manuscript Received 10/09/2023; Revised 18/10/2023; Accepted 25/10/2023

Abstract

A road section at Bhalupahad, Syangja of Siddhartha highway was investigated to characterize the rock mass, identify the potential slope failure modes, and determine the stability condition and the major governing factors. The site comprises steep slopes, faces intense rainfall during monsoon periods and falls in a highly active seismic zone. The attitudes of the hill slope and the major discontinuities were measured at 16 different locations and analyzed using stereographic projection. The data was plotted by using Dips 6.0 software. Plane, wedge, and toppling failure modes are possible in the study area. Besides, the Factor of Safety (FOS) for plane and wedge modes of failure has been calculated using Slide2 software. An end-anchored bolt has been installed to increase the FOS at the unstable slope locations. The FOS has increased to 1.3, 1.23, 1.21, 1.28, and 1.29 after support installation, which was 0.43, 0.71, 0.4, 0.55, and 0.57 before giving support at locations 1, 4, 8, 12 and 14 respectively. Rocks were identified as fair to good quality according to Rock Mass Rating (RMR) and partially stable to stable according to Slope Mass Rating (SMR). The results obtained from RMR and SMR agree well with each other and the real slope conditions. Q-slope suggests a slope angle of 60^0-65^0 with a respective Q-slope value of approximately 1.0. The orientation of discontinuities, steep topography, intense rainfall and human intervention are the main causes of slope failures.

Keywords: Kinematic Analysis; Rock Slope Stability; RMR; SMR; Q-slope; Limit equilibrium method; Factor of safety.

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1. Introduction

Hills and mountains of the world frequently face slope instabilities. So, attention has been paid to solving these problems, and several studies have been conducted worldwide [1]. Nepal also faces the problem each year, causing huge loss of lives and property. The issue becomes more critical when concerned with road construction, especially in steep and mountainous regions [2]. The slope fails if the driving forces along an exposed discontinuity surface of either natural or cut slope exceed the shear resistance of that discontinuity. The shear resistance of any discontinuity surface depends on the persistence, roughness, alteration, infilling conditions, groundwater condition, and magnitude and frequency of seismic activities. More importantly, the topographic surface of steep valley side slopes in the Himalayan region is being modified due to development activities such as the construction of roads, agricultural excavation, construction of hydropower projects, etc., which enables large-scale discontinuities to expose (daylight) increasing risk of slope failures [3].

Slope stability analysis assesses the safe and economical design of natural and man-made slopes. It has many applications, such as road cuts, mining, excavations, tunnels, foundations and retaining walls. It aims to identify the endangered slope sections, investigate potential slope failure modes and design optimal slopes concerning safety and economy. Understanding the underlying mechanisms (geological processes, stratigraphy, geomorphology petrography and earthquake) is utmost to designing a stable slope. The geometry of the slope, the attitude of discontinuities, failure plane orientation, and groundwater conditions are the internal governing factors, while human activities and seismicity are the external governing factors causing slope failures [4]. Among all these parameters, the shear strength of discontinuities is the most important one and is governed by different geological and non-

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geological parameters [3].

Slope stability analysis techniques include empirical, analytical, and numerical methods. Plane, wedge and toppling are the common forms of slope failures in the rock mass [5]. The slope stability analysis can be done in four steps i) Rock mass classification to know the stability condition; ii) Kinematic analysis to determine the failure modes; iii) Determining the safety factor by limit equilibrium method; and iv) Numerical modelling.

2. Study area

Bhalupahad is located at Phedikhola Gaupalika of Syangja district. It is 27 km southwest of Pokhara along the Phedikhola-Naudanda road section of the Siddhartha highway. The area lies in the Lesser Himalayan region which comprises sedimentary and metasedimentary rocks (Figure 1). The rock types found in the area are Phyllite, Quartzite, and Metasandstone of the Naudanda formation. The study area Bhalupahad is shown in the geological map by [6] (Figure 1).

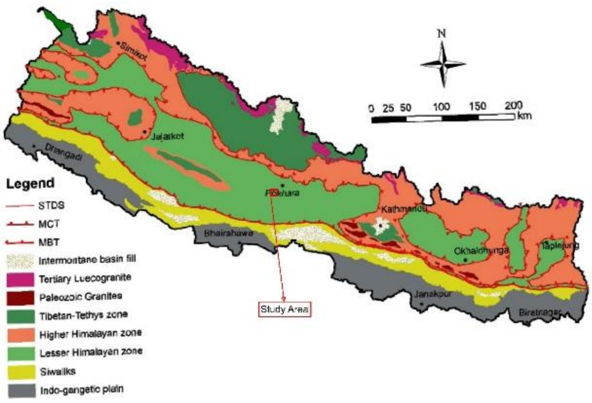

Figure 1: Location Map of the study area. [6]

3. Literature Review

The design and analysis of structures like tunnels, foundations and road cuts require a proper understanding of rocks' engineering geological and mechanical properties. These properties include the shear strength, permeability, and deformability, which depend more on the nature of discontinuities than on the properties of the intact rock. Rock mass failure generally occurs through discontinuities. This is controlled by the shear behavior of the discontinuities. We can estimate the shear strength using the empirical law of basic friction angle given by [7] (Equation 1).

$$\tau = \sigma_n \times \tan\left[JRC \times \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \phi_b\right] \dots\dots (1)$$

where,

τ is peak shear strength (KPa)

σ_n is effective normal stress (KPa)

JRC is the joint roughness coefficient

JCS is Joint wall compressive strength (KPa)

ϕ_b is basic friction angle in degree

According to [3], the design of a rock slope involves three steps: 1) Defining the potential stability problem, 2) Assessing the input parameters, and 3) Calculating the safety factor.

4. Methodology

Detailed field mapping, data processing and stability analysis techniques (Figure 2) were employed to fulfill the study's main objective. The study of cut slopes has been accomplished in three substantial steps.

i)Desk study: Topographic maps, geological maps, reports, journals, and news articles were studied and literature related to rock slope engineering was reviewed to learn how to conduct the slope stability assessment before the field visit.

ii) Field investigation: Topography, geology, and groundwater conditions were identified. Hill slope geometry and attitude of joints were measured. Data required for rock mass classification were collected through extensive geological field mapping.

iii) Slope stability analysis: Slope stability analysis has been conducted in three steps as

a) Rock mass classification: Rock Mass Rating (RMR), Slope Mass Rating (SMR) and Q-slope method of rock mass classification systems have been evaluated for the stability assessment in the study area. The stability conditions have been identified and results of various rock mass classification systems have been compared.

b) Kinematic analysis: Kinematic analysis has been done using Dip's software (Rocscience) where hill slope geometry, the attitude of discontinuities and friction angle have been used as the input parameters.

c)Limit equilibrium analysis: Limit equilibrium analysis has been performed using Slide software (Rocscience). Bishop's method has been used where the surface type is circular and the grid search method is used for the surface options. Barton and Bandis mode of failure (Equation 1) has been used with joint roughness coefficient (JRC), joint wall compressive strength (JCS), friction angle(ϕ) and unit weight (γ) as the input parameters. The hill slope geometry and attitudes of discontinuities were measured. Schmidt hammer was used to determine the uniaxial compressive strength (UCS). The amplitude of asperities of joints was measured using a folding scale and ruler. JRC and JCS were estimated from the graph given by [7]. Data for rock mass classification were taken and noted in the field book as per [8, 9, and 10]**.** Rock types, geological structures and groundwater conditions were identified.

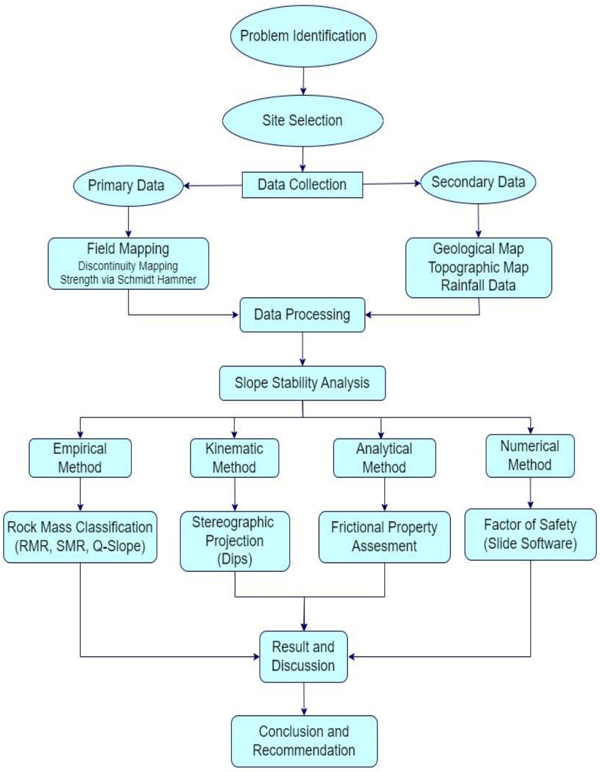

Figure 2: Methodology Chart

5. Results and Discussion

Kinematic analysis was performed using Dips software, showing mixed mode (plane, wedge and toppling) failures in the study area (Figure 3). Rock mass classification was done using RMR, SMR, and Q-slope methods. From the RMR classification, the rock quality was found to be fair to good, with a maximum RMR value of 77 at locations 2 and 14 and a minimum RMR value of 53 at location 13. Similarly, SMR classification showed that the rock mass is partially stable to stable, with a maximum SMR value of 76 at location 8 and a minimum SMR value of 53 at location 13. The stability condition was also observed using Q-slope, the special method for assessing rock slope stability. Q-slope suggests a stable slope angle of 60^0-65^0 with a respective Q-slope value of approximately 1. The stability conditions obtained from the Q-slope method matched well with the actual field conditions. It proves the efficiency of using the Q-slope method for the rock slope stability assessment (Table 2) Besides, the limit equilibrium analysis was done using Slide software to find out the FOS.

The factor of safety was found to be less than one (unstable) at 10 locations, greater than one (stable) at 4 locations and one (critical) at 2 locations. The results obtained from the empirical methods nearly match each other and the site's conditions.

Rock types found in the area are mostly quartzite. Somewhere there is the presence of soft (Phyllite) rock in between hard (quartzite) layers. The hill slope of the road cut has a dip amount greater than 60^0 at all locations. Frequently, the rock mass has three sets of discontinuities, which govern the failure pattern.

The results obtained from different methods have been presented in Table 1 below.

Table 1: Results of RMR and SMR classification

Loc	**Rock Mass Rating**				**Slope Mass Rating**		
	RMR	**Class**	**Rock Quality**		**SMR**	**Class**	**Stability**
1	71	II	Good		60	III	Partially stable
2	77	II	Good		73	II	Stable
3	69	II	Good		65	II	Stable
4	65	II	Good		61	II	Stable
5	70	II	Good		69	II	Stable
6	64	II	Good		63	II	Stable
7	70	II	Good		70	II	Stable
8	76	II	Good		76	II	Stable
9	67	II	Good		67	II	Stable
10	62	II	Good		58	III	Partially stable
11	67	II	Good		72	II	Stable
12	59	III	Fair		54	III	Partially stable
13	53	III	Fair		53	III	Partially stable
14	77	II	Good		71	II	Stable
15	64	II	Good		64	II	Stable
16	59	III	Fair		59	III	Partially stable

The Rock Mass Rating (RMR) showed good-quality rock at most locations and fair-quality rock at some locations. Similarly, the slope mass rating showed the rock mass as partially stable to stable. Comparing the results of RMR and SMR as indicated in Table 1, we can see that the locations with fair-quality rock are partially stable, whereas those with good-quality rock are stable. From this, we can say that there is a strong agreement between the results obtained from both methods.

Table 2: Results of Q-slope and Kinematic method.

Loc	Q-slope Method			Kinematic method
	Q-slope	β	Stability Condition	Modes of Failures
1	1.18	66.45	Stable	Wedge
2	1.05	65.42	Uncertain	Planar
3	1.05	65.42	Uncertain	Wedge
4	1.18	66.45	Stable	Wedge
5	1.05	65.42	Uncertain	Wedge
6	1.05	65.42	Uncertain	Wedge
7	1.18	66.45	Stable	Planar
8	1.05	65.42	Uncertain	Wedge
9	1.18	66.45	Stable	Wedge
10	1.18	66.45	Stable	Toppling
11	1.18	66.45	Stable	Wedge
12	1.18	66.45	Stable	Planar
13	1.18	66.45	Stable	Wedge
14	1.05	65.42	Uncertain	Planar
15	1.18	66.45	Stable	Wedge
16	1.18	66.45	Stable	Planar

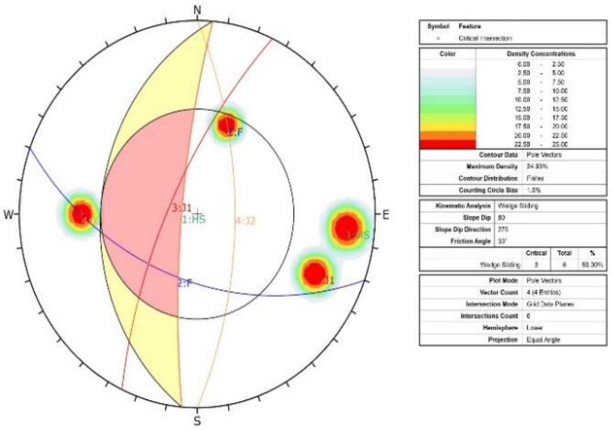

Figure 3: Stereonet Plot Showing Wedge Failure at Location 3.

The Q-slope method (Table 2) showed that most locations were stable and some were uncertain. At locations 2 and 3, cracks can be seen in the field. Besides, at locations 2 and 3, thin phyllite bands can be observed between quartzite rock. Failure can be observed at location 8, as shown by the Q-slope method results in Table 2. Locations 5 and 6 have uncertain stability conditions and comprise highly jointed rocks. Most locations in the field have cut slope angles greater than 65^{0}. However, the Q-slope result suggests a stable angle of 60^{0}-65^{0} with a Q-slope value of approximately 1.

Kinematic analysis was done using Dips software, which showed a mixed failure mode in the study area. The result of the kinematic analysis at different locations agrees with the modes of failure observed in the field. Figure 3 shows the wedge failure at location 3.

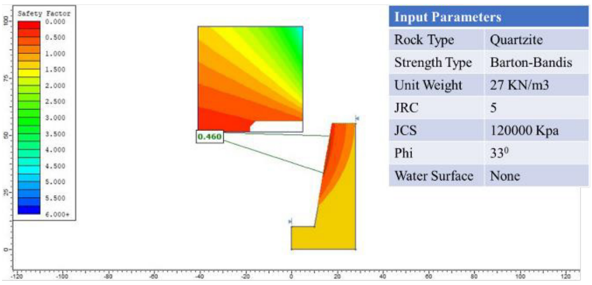

Figure 4: Results from Slide Software showing factor of safety at location 3.

In addition, analytical assessment has been carried out using numerical modeling program called "Slide" to find out the factor of safety of the slope at all the locations. Slide is a software developed by Rocscience and is based on 2D LEM. A simple geometrical model has been used for the analysis. Bishop's method has been used where the surface type is circular and grid search method is used for the surface options.

Table 3: Results from Slide software showing factors of safety at various locations.

Location	H (m)	JRC	JCS (MPa)	FOS	Remarks
1	40	6	70	0.43	Unstable
2	50	3.5	120	0.52	Unstable
3	45	5	120	0.46	Unstable
4	50	3.5	140	0.5	Unstable
5	55	5	130	0.55	Unstable
6	60	8	90	1.2	Stable
7	40	5.5	160	1.3	Stable
8	55	2.3	95	0.51	Unstable
9	45	2.5	150	0.44	Unstable
10	40	3.5	150	0.3	Unstable
11	10	8.5	43	1.13	Critical
12	50	3.5	52	0.67	Unstable
13	50	10	31	1.01	Critical
14	25	2.5	65	0.84	Unstable
15	35	8	69	1.2	Stable
16	15	3	40	1.4	Stable
$\gamma = 27\frac{KN}{m^3}$			$\phi = 33^0$		

Further, it has been used to support the unstable slope (FOS<1) locations to increase the FOS, making the slope stable. The 10 locations showed FOS<1, and 6 locations showed FOS>1. The material properties have been set as per the Barton-Bandis strength model with JRC, JCS, γ, and ϕ as the input parameters. One such result example is shown in Figure 4. Details of the factor of safety of all studied locations are presented in Table 3.

Among various types of support in the slide software, an end anchored bolt of length 6m-8m has been installed at an angle of (-10^0) from the horizontal and 1m spacing with varying anchor capacities to increase the FOS. One of the results from Slide software showing FOS before and after support is shown in Figures 5 and 6.

Table 4: Result from slide software before and after support

Location	FOS (Before support)	FOS (After support)	Anchor capacity (KN)	Length (m)
1	0.43	1.3	200	6
4	0.71	1.23	250	6
8	0.4	1.21	750	8
12	0.546	1.28	350	8
14	0.572	1.29	500	8
Support properties: Spacing – 1m; Angle from horizontal – (-10^0); Force application – Active method.				

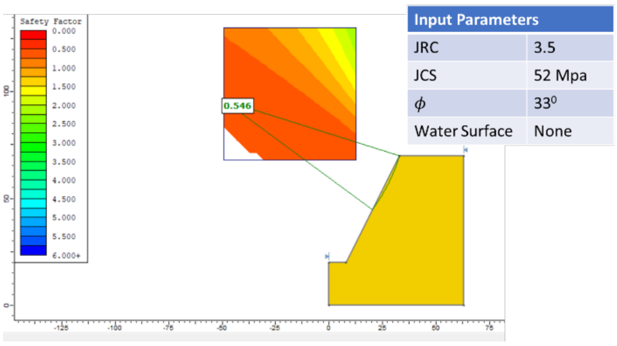

Figure 5. Location 12 before support

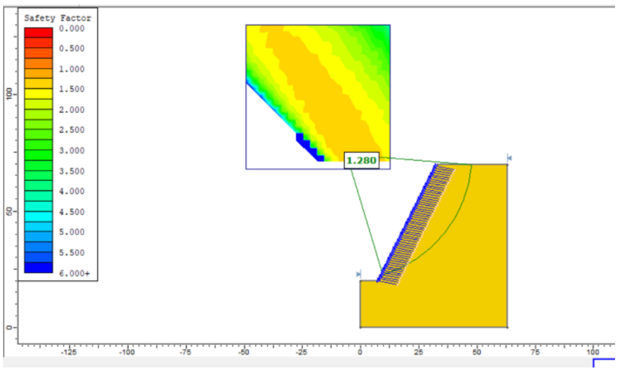

Figure 6. Location 12 after support

6. Conclusions

Quartzite, phyllite, and metasandstone are the rock types found in the area. Empirical methods, kinematic method and Limit Equilibrium method have done stability analysis. As per the kinematic analysis, the study area has possibilities for mixed failure modes (plane, wedge and toppling). Rock Mass Rating (RMR) showed the fair to good quality rocks. The stability condition, as given by Slope Mass Rating (SMR), is partially stable to stable. Bolt and anchor have been suggested as suitable support measures as per the guidelines given by [9]. The results show a strong agreement between the results obtained from RMR and SMR. Q-slope suggests a slope angle of 60^0-65^0 with a respective Q-slope value of approximately 1.0. Slide software has been used to determine the FOS and support installation. An end-anchored bolt has been installed to increase the FOS at the unstable slope locations. The FOS has increased to 1.3, 1.23, 1.21, 1.28, and 1.29 after support installation, which was 0.43, 0.71, 0.4, 0.55, and 0.57 before giving support at locations 1, 4, 8, 12, and 14 respectively. The hill slope of the road cut has a dip amount greater than 60 degrees at all locations. Frequently, the rock has three sets of discontinuities, which govern the failure pattern. The orientation of discontinuities, variable topography, occurrence of extreme rainfall events, and human intervention are the main causes of slope failures.

7. Recommendations

Numerical modeling based on FEM is recommended for further study. The effect of groundwater and earthquakes must be considered to determine overall slope stability. Slope stability analysis using different types of support and various support properties is suggested for better results. Wire mesh protection is recommended to prevent rolling blocks.

Acknowledgment

This work is a part of a thesis for an MSc in Rock and Tunnel Engineering. I am grateful to all the direct and indirect helping hands.

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