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Stability assessment of desander cut slope of Seti Khola Hydropower Project

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ABSTRACT

Due to steep topography in the Himalaya, opening space for the development of infrastructures involves excavation of hillside slopes which possesses certain degree of risk associated with failure. This paper aims to assess the stability of the rock slope excavated for the placement of desander basin of the Seti Khola Hydropower Project (22 MW) located in Lekhnath, Kaski district of Gandaki Province. The height of the cut slope is about 60 m and is the challenging part of the construction work of this project. The slope is cut in the rock mass belonging to highly schistose graphitic phyllite intercalated with meta-sandstone at the upper part of the slope. To conduct a detailed stability assessment, the discontinuities, and geometric characteristics have been evaluated by field mapping. A three dimensional (3D) geological model has been generated to represent the geometric properties of discontinuities and the cut slope incorporating failure plane. The mechanical characteristic of the intact rock is established through literature review whereas the rock mass properties have been assessed using different equations. Rock mass quality has been assessed by using Rock Mass Rating (RMR) method of rock mass classification. RMR values are then correlated into Slope Mass Rating (SMR) incorporating different factors of slopes as per the site conditions. Further, kinematic analysis has been carried out using geometric and discontinuity properties to evaluate the structurally controlled failure. The influence of groundwater and earthquake has been considered while determining the shear strength of sliding surface. Finally, stability assessments have been carried out empirically, analytically and two dimensional (2D) numerical modelling.

Keywords: Discontinuity properties, 3D model, groundwater, earthquake, shear strength, stability assessment

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INTRODUCTION

Seti Khola Hydropower Project is designed as Run-off River Project with an installed capacity of 22 MW. For the construction of desander basin, the right bank slope of about height 60 m and a length of 100 m is being excavated in a rock formation consisting highly schistose phyllite with meta-sandstone. The stability of the cut slope is hence critical. Stability of rock slope is dependent on the slope topography, orientation of discontinuity planes, shear strength of discontinuities, groundwater and stress conditions, and the seismic acceleration magnitude. The factors that influence the shear strength of the discontinuities are the frictional properties associated to roughness, and infilling condition of the main failure plane and the presence of groundwater (Panthi, 2021). In addition, the geometry of the cut slope and seismic acceleration caused by earthquakes (Wyllie and Mah, 2004) or vibration caused by blasting also influence in the overall stability of a cut-slope. According to Nilsen and Palmstørm (2000) the rock slope stability assessment typically involves a three-step procedure consisting of (1) definition of potential problem, (2) quantification of input parameters and, (3) calculation of stability.

This manuscript assesses rock slope stability of the desander slope. To do so, a comprehensive field mapping was carried out to map orientation and condition of the discontinuities. Geometric information has been gathered and evaluated and mechanical properties of intact rock and rock mass have been assessed and estimated using relevant literature. Rock mass quality has been assessed in the field using the Rock Mass Rating (RMR) method of rock mass classification proposed by Bieniawski (1989). RMR values are then correlated into Slope Mass Rating (SMR) which is an empirical tool suggested by Romana (1985) for the assessment of rock slope. Kinematic analysis has been carried out using geometric and discontinuity properties to evaluate the structurally controlled failure. The shear strength of rock mass is calculated semi-empirically by using Barton and Bendis (1990) failure criteria. The detailed stability assessment has been carried out using both limit equilibrium method and numerical analysis.

GEOLOGY AND PROBLEM DEFINITION

Pokhara Valley lies in the Lesser Himalayan Zone of western Nepal. The headwork structures are located on the right bank of the Seti Khola of the area and is surrounded by low-grade metamorphic rocks of the Kuncha Formation consisting of phyllites intercalated with meta-sandstone. In addition, the left bank of the area is covered with Pokhara Formation (Fig. 1). The height of the cut slope is about 60 m which is among the challenging part of construction work for this project.

The slope is under construction and the upper part of the slope is supported with mess shotcrete and 3 m long bolting. After excavation and application of the support and further excavation downward, a tension crack was appeared on the back side of the excavation. In addition, cracks are appeared along the slope face indicating a need for comprehensive analysis of the slope. The location of tension cracks and engineering geological properties have been mapped during fieldwork which is used as input for the stability assessment. The cut slope with the support measures is shown in Figure 2.

A 3D geological model has been developed as indicated in Figure 3 where the cut slope and development of cracks are indicated.

INPUT PARAMETERS FOR ANALYSIS

The mapped orientations of discontinuities are shown in Table 1. The intact rock parameters are taken from relevant literature review (Panthi, 2006) and (Panthi and Basnet, 2022), and rock mass parameters were calculated and tabulated in Table 2. The GSI was measured in the field. The input for the frictional properties of the discontinuities have been mapped and estimated at the field and are presented in Table 3. The mechanical properties of applied support have been estimated using relevant literatures. The stress components have been taken based on vertical stress only as it is near the surface. The topographic effect is included in the geometry for the numerical modelling. Rock mass strength is calculated using Panthi (2006) for highly schistose, foliated, thinly bedded and anisotropic rocks and the relation is in Equation 1:

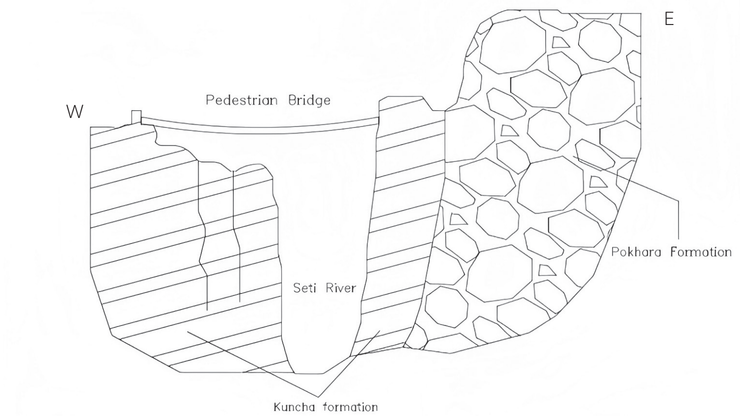

Fig. 1: Section of study area showing regional formations on the left and right bank of the Seti Khola. (Inside figure, formation to Formation, Seti River to Seti Khola)

Fig. 2: Cut slope face of the desander basin in project area.

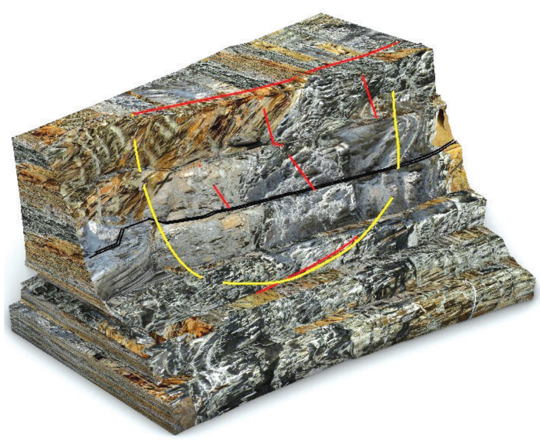

Fig. 3: Geological model of cut slope for the desander basin.

$$\sigma_{cm} = \frac{\sigma_{ci}^{1.5}}{60} \quad (1)$$

Groundwater

Based on the rainfall chart and data retrieved from the Department of Hydrology and Meteorology (DHM), Meteorological Forecasting Division of Nepal, the maximum daily rainfall of 97.6 mm was recorded on August 30, 2021. Thus, we can assume that the slope gets fully saturated during monsoon season which can be considered as worst-case scenario for the analysis.

Seismic effect

Repeated occurrence of prehistoric earthquakes of different scales causes persistent ground acceleration, which could instigate the extension of pre-existing discontinuities, formation of tension cracks at the upper slope, formation of many other joints and cracks in the rock mass, and loosening on the upper layer rock mass (Panthi, 2021). For the analysis, a seismic coefficient of 0.02 was considered be instigated by blasting since there were no significant earthquake movement for last two years. However, for the long-term assessment of the slope should use higher seismic coefficient should be used.

Table 1: Discontinuity and properties.

S.N.	Dip (°)	Dip direction (°)
F	17	245
J1	54	133
J2	67	216
J3	69	351
Cut slope	61	172

Table 2: Intact rock and rock mass properties.

UCS of intact rock, σ_{ci} (Mpa)	20	
Modulus of elasticity, Ei (Mpa)	12000	
Poisson's ratio, μ	0.25	
Rock mass strength, σ_{cm} (Mpa)	1.49	
Failure criteria	Generalized Hoek Brown	
	Peak	Residual
Geological strength index GSI	26	14
Intact rock constant mi	10	7
mb	0.712	0.062
s	0.0002686	0.0000039
a	0.5292	0.5653
Rock deformation modulus (Erm)	761.8	285.6

Table 3: Frictional properties for LEM input.

Slip criterion	Barton-Bandis
Joint compressive strength JCS (Mpa)	1.3
Joint roughness coefficient JRC	5.1
Residual friction angle (degrees)	26

METHODOLOGY AND RESULTS

Kinematic analysis

The kinematic analysis was performed using Dips software (Rocscience) using the information shown in Table 1. The kinematic analysis indicated a planar sliding along J1 as shown in Figure 4, wedge along J1 and J2, flexural toppling along J3, and direct toppling along the foliation plane (F). Since there is a formation of slip surface along the slope a planar sliding without lateral limits were used for further analysis as a tension crack is seen in the upper slope.

Slope mass rating

RMR ranges from 24 to 53, SMR ranges from 16 to 45 and GSI ranges from 19 to 48 (Table 4).

Analytical assessment

The input parameters associated to frictional properties of the joints and geometric conditions (Fig. 6) are evaluated using data from field mapping and literature study. The stability assessment has been made using assessed joint properties, geometry of the slope, groundwater condition and seismic acceleration.

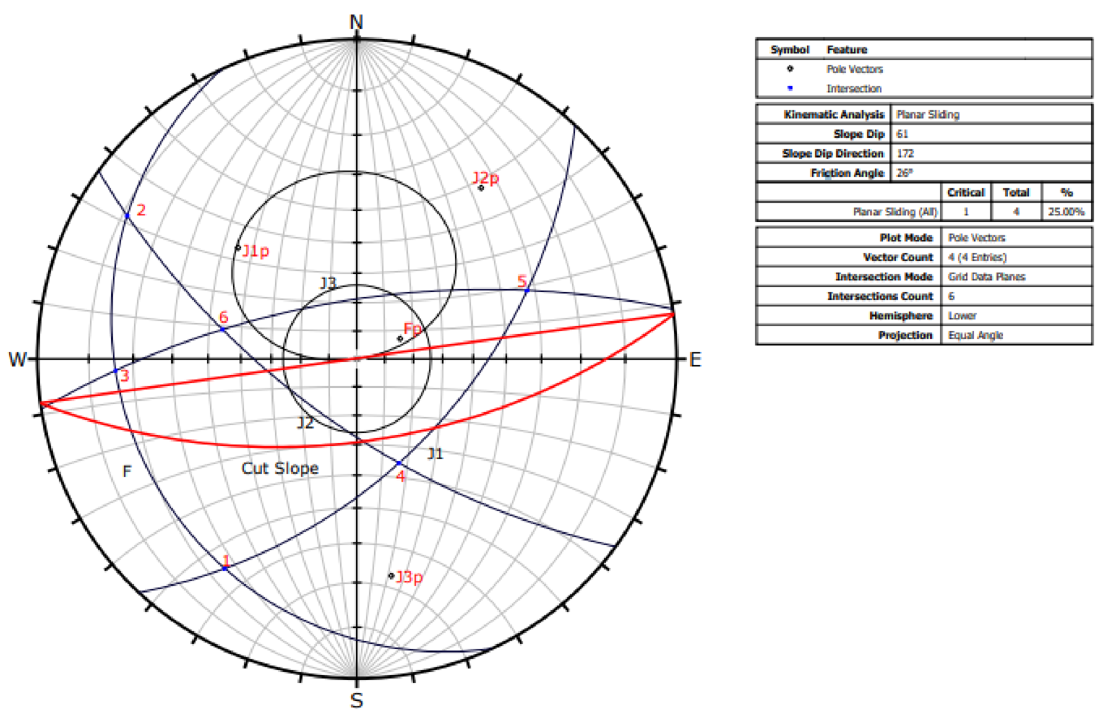

Fig. 4: Kinematic analysis using Dips 7.0.

Table 4: Results of SMR calculation for each block (Also see Fig. 5).

Block No.	SMR class	Description
18	III	Normal
4, 6, 7, 8, 12, 13, 14, 16, 17	IV	Bad
1, 2, 3, 5, 9, 10, 15	V	Very Bad

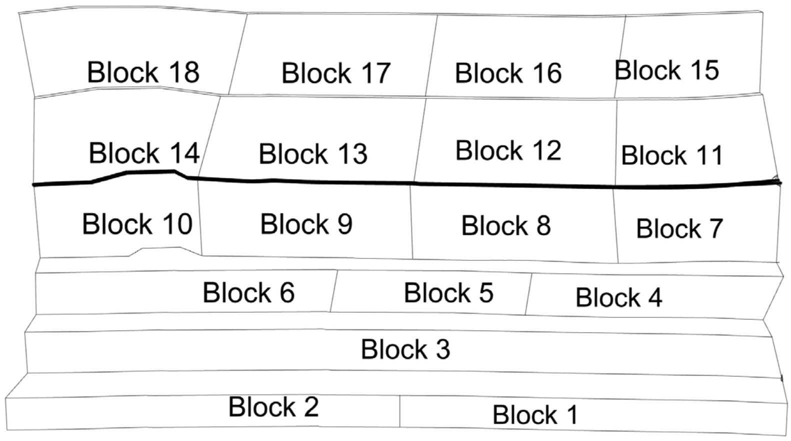

Fig. 5: Block division for calculation of slope mass rating.

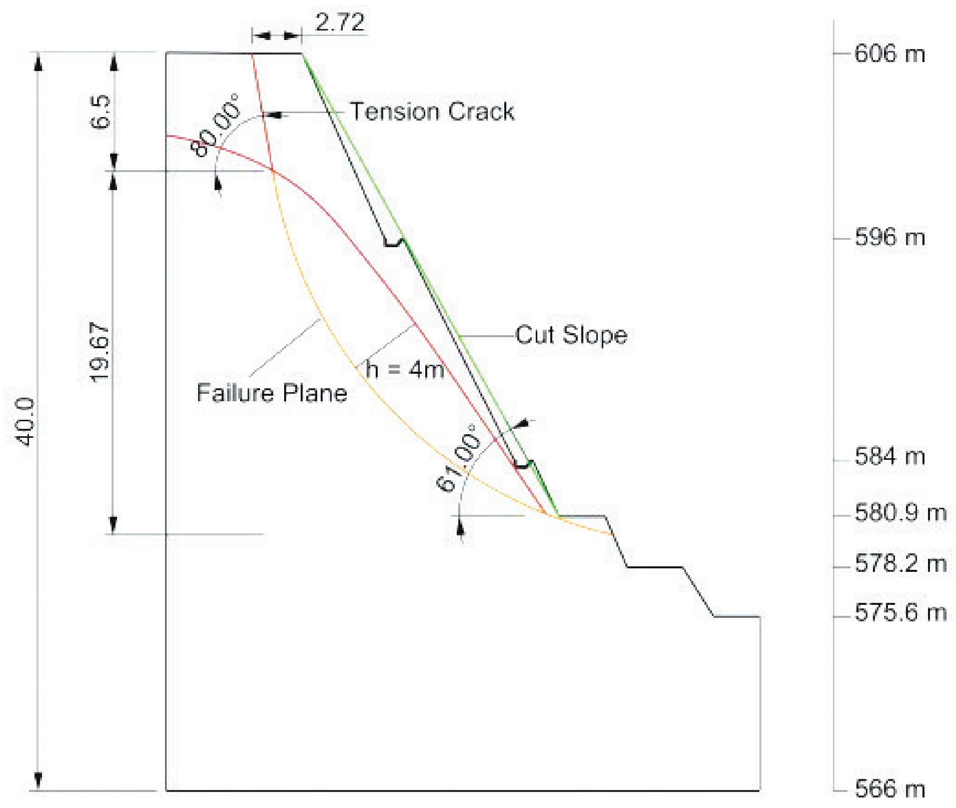

Fig. 6: Geometric condition of the slope.

The shear strength of the sliding surface is determined using Barton and Bendis (1990) criteria.

$$\tau = \sigma_n \times tan\left(\phi_b + JRC \times log_{10}\left(\frac{JCS}{\sigma_n}\right)\right) \quad (2)$$

Where the component excluding normal stress (σ_n) gives active friction angle and the normal stress is calculated using Panthi (2021) as given:

$$\sigma_n = \frac{\left(W \times cos\varphi_p - U - F_a \times sin\varphi_p\right)}{\left(\frac{H}{sin\varphi_p}\right)} \quad (3)$$

φ_p is failure plane angle, U is water pressure, W is weight of overlaying mass and H is Height of the slope. The results of the calculation are shown in Table 5.

Stability assessment using Slide

The Slide software (Rocscience) was used to find out the failure surface using the ordinary slice method. The phyllite rock mass has been modelled for the worst-case scenario consisting of the presence of tension crack, groundwater and seismic acceleration coefficient discussed that already discussed. The assessment gave a factor of safety of 0.56 where the support measures applied along the slope has been included. The results of the analysis are given in Figure 7 and Table 6.

Table 5: Results of analytical assessment.

Normal stress (σ_n) (kN/m^2)	39.7
Active friction angle (φ_α) (degrees)	33.7
Shear strength (τ) (MPa)	26.5
Factor of safety	0.31
Remarks	Unstable

Table 6: Factor of safety with different scenario.

Consideration	Factor of safety
seismic effect only	0.562
Groundwater effect only	0.582
Both groundwater and seismic effect	0.562

Analysis using Phase2

An important step in analysing the stability of rock slopes using Phase2 is to decide whether to use an equivalent continuum approach or a discontinuum approach for numerical modelling. Among the two, the equivalent continuum approach is used here to assess strength factor where rock mass is taken as a homogenous medium. It is logical to use an equivalent continuum approach for a rock mass having lower Q or RMR values. The common start of the stability analysis of a rock slope where the rock mass is highly schistose is to use a continuum model.

Hence, the rock mass was modelled as an elastic-perfectly plastic material. 2D six-nodded plane strain triangular elements were used to discretize the rock slope. Lateral boundaries were fixed in the x-direction and the bottom boundary was fixed in y directions. At the corners, boundaries were fixed in both directions. The Gravity field stress has been used where the ratio of horizontal to vertical stress has been calculated based only on vertical stress and horizontal stress as a component of vertical stress due to the Poisson's ratio. The input parameters given in Table 3 are used for analysis. The excavation was done in four stages. Standard beam liner type (shotcrete) of thickness 0.1 m and Rock Bolts of 3 m long have been used as rock support. Generalized Hoek Brown Failure criteria (Hoek et al., 2002) is used for the analysis. The results are shown in Table 7. The failure surface considering both groundwater and seismic effect is shown in Figure 8. Phase2 performs a systematic search for strength reduction factor (SRF) starting from a value of unity to the value that will just initiate failure in the slope. The critical value of SRF obtained in the process can be taken as the factor of safety (FOS).

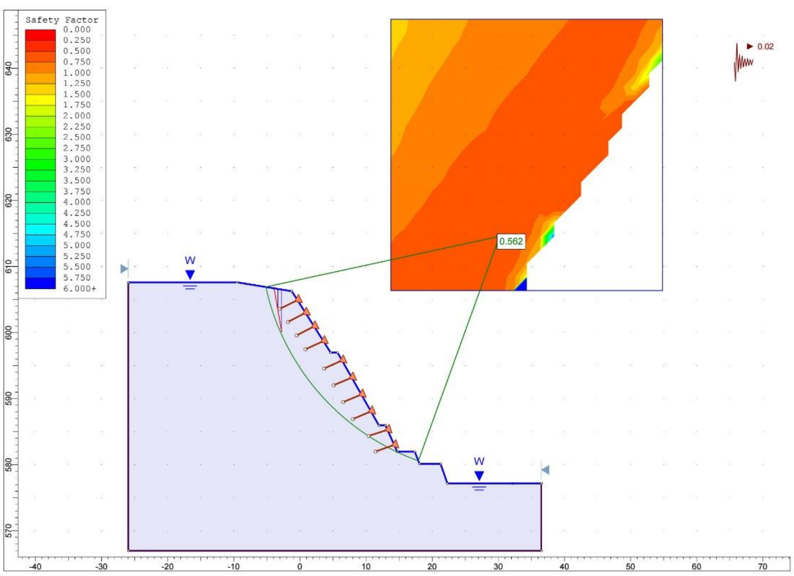

Fig. 7: Result of Slide analysis considering both groundwater and seismic effect.

Table 7: Result from Phase2 analysis.

Consideration	Factor of safety
Seismic effect only	1.2
Groundwater effect only	1.37
Both groundwater and seismic effect	1.19

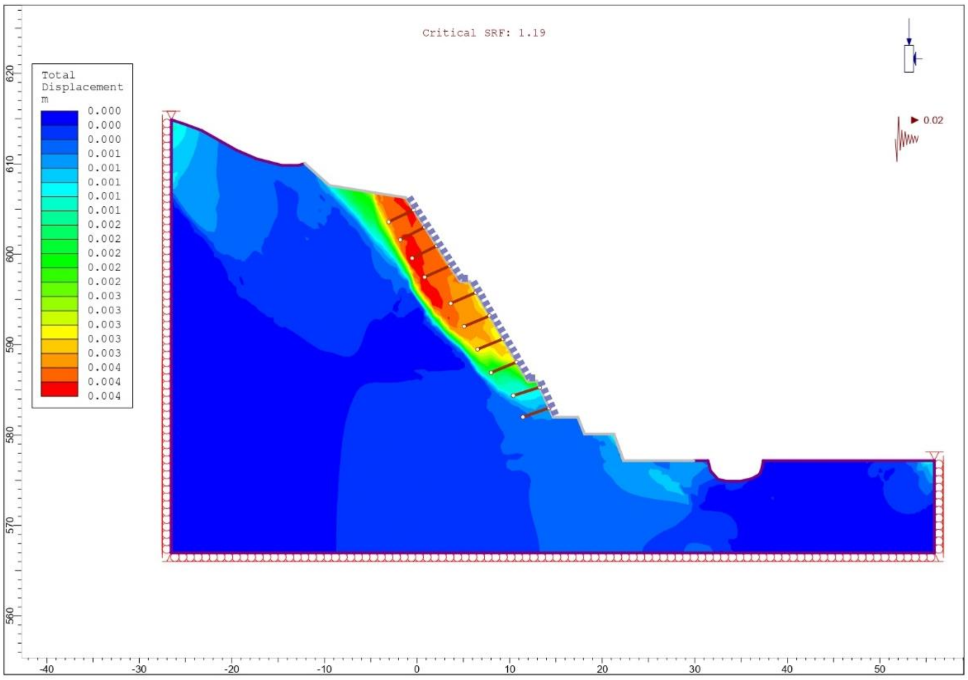

Fig. 8: Result of Phase2 analysis considering both groundwater and seismic effect.

CONCLUSIONS

The different methods have been used to assess the potential stability of the desander rock slope at Seti Khola Hydropower Project. The kinematic analysis and empirical assessment using SMR gave possibility to assess the type of failure. The geometric assessment made it possible to quantify volume of failure mass. The field mapping helped to assess discontinuity condition and frictional properties prevailing in the slope. All type of assessment indicated that the rock slope after first stage of excavation is in critical condition with a factor of safety close to one or less than one.

The results presented in this manuscript are based on relatively short field mapping and assessment of rock mechanical properties using literature. Therefore, the assessment has certain degree of uncertainties. It is emphasized here that, after the tension crack development at the top of the slope, further unloading has been made by excavating at the upper part of the slope and more rock support measure has been provided. Project has plan to carry out extensive stability assessment to ascertain the long-term stability of the cut-slope.

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