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Rock slope deformation analysis of the powerhouse cut-slope at Middle Bhotekoshi Hydroelectric Project in Sindhupalchok District, central Nepal

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ABSTRACT

This paper elaborates the rock slope deformation analysis in a complex rock mass i.e., metamorphic rocks. At the powerhouse of the Middle Bhotekoshi Hydroelectric Project, Sindhupalchok, Nepal, the rock slope deformation has occurred as a result of excavation of natural rock slope turning into the cut-slope. The deformation yielded by different causes were studied and analyzed by kinematic analysis, inclinometer data combining with numerical modeling. For the study and analysis of the cut-slope, geotechnical data were collected from the existing rock types of the cut-slope. At first, the kinematic analysis was carried out by using the stereonet plot in DIPS. The core logs of investigation time were reviewed and tried to prepare the geological model of this part. The finite element method was used to analyze the stability of the rock cut-slope based on the geotechnical data. Similarly, the inclinometer recorded data were used to compare with the analyzed deformation data and tried to find out the weak zone within the cut-slope. The kinematic analysis showed that the rock slope has the least probability of failure. The result showed that there was tolerable deformation on the slope based on inclinometer data but failure was observed at PSIN-1 where the weak zone is present. The deformation at PSIN-1 was found to be in the thin ductile deformed zones where rock characteristics were different which was considered not operative for the slope stability.

Keywords: Cut-slope, deformation, kinematic analysis, inclinometer, numerical modeling

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INTRODUCTION

The rock cut-slope development is one of the adopted methods for the ground preparation to construct different hydraulic structures within the hydroelectric projects in the mountain region where plain land is not available. While developing required rock cut-slope, certain difficulties sometimes unpredicted issues may arise because of the topography and complicated geology of the Himalayan Region. The stability of the developed rock slope is mainly controlled by different parameters i.e., slope angle and its geometry, lithology of the area, rock mass properties, different discontinuity parameters, etc. Furthermore, stabilization of the cut-slope also depends on the modified stress path followed after excavation and the material's strength. One such case was studied at powerhouse cut-slope of the Middle Bhotekoshi Hydroelectric Project located at the Sindhupalchok District. The study site geologically belongs to the schist of the Kuncha Formation of Central Nepal Lesser Himalayan Zone and the study area lies between latitude 27˚49'07" N to 27˚49'11" N and longitude 85˚52'48" E to 85˚52'52" E (Fig. 1).

Designing tectonically deformed rock is a challenging task. Strain development in modified slope is the function of material properties, discontinuity properties, lithology, and evaluation of the stability of the modified slope became more difficult due to the variance in attributes. A close and detailed study was carried out to understand the cause of the deformation that appeared in a certain section of the slope. Jointed rocks are prone to slacking due to unloading of confining stress on internal joints during excavation (Barbero and Barla, 2010, Bonini et al., 2013). In rock slope stability analysis, the failure mechanism is often assumed to be associated with the sliding of rock along pre-existing discontinuities (Romer, and Ferentinou, 2019). Therefore, the stability of the cut slope is associated with the strength of the discontinuity surface embedded in the rock mass of the slope and the strength of the rock bridge of the joints. Sometimes some information is missed during the investigation and that becomes disastrous. In the case of Vaiont rockslide, Müller (1968) reported several original reports did not consider the clay inter-beds along the failure surface of the slide. But many other authors recognized the layers' significance in controlling the kinematics and dynamics of the Vaiont rockslide (Ventisette et al., 2015).

The cut-slope comprises pelitic and psammitic schists layered unevenly and undulating with several quartz veins. Distributions of these veins are uneven and both rock types pose different geo-mechanical behaviours. The shift in stress route always looks for the weak zone to pass against the material behavior or strain, which results in cut-slope deformation, adding further complexity to the behavior that must be understood. Rock mass classification is a useful tool for rock slope stability analysis and Fereidooni et al. (2015) have used rock mass classification for rock slope stability analysis.

The rock cut-slope generally exhibits instability problems due to combination of the nature of the foliation and joints, the direction of the cut-slope, removal of overburden, groundwater conditions, etc. Therefore, careful and systematic observation of the cut-slope is very essential to prevent future instability

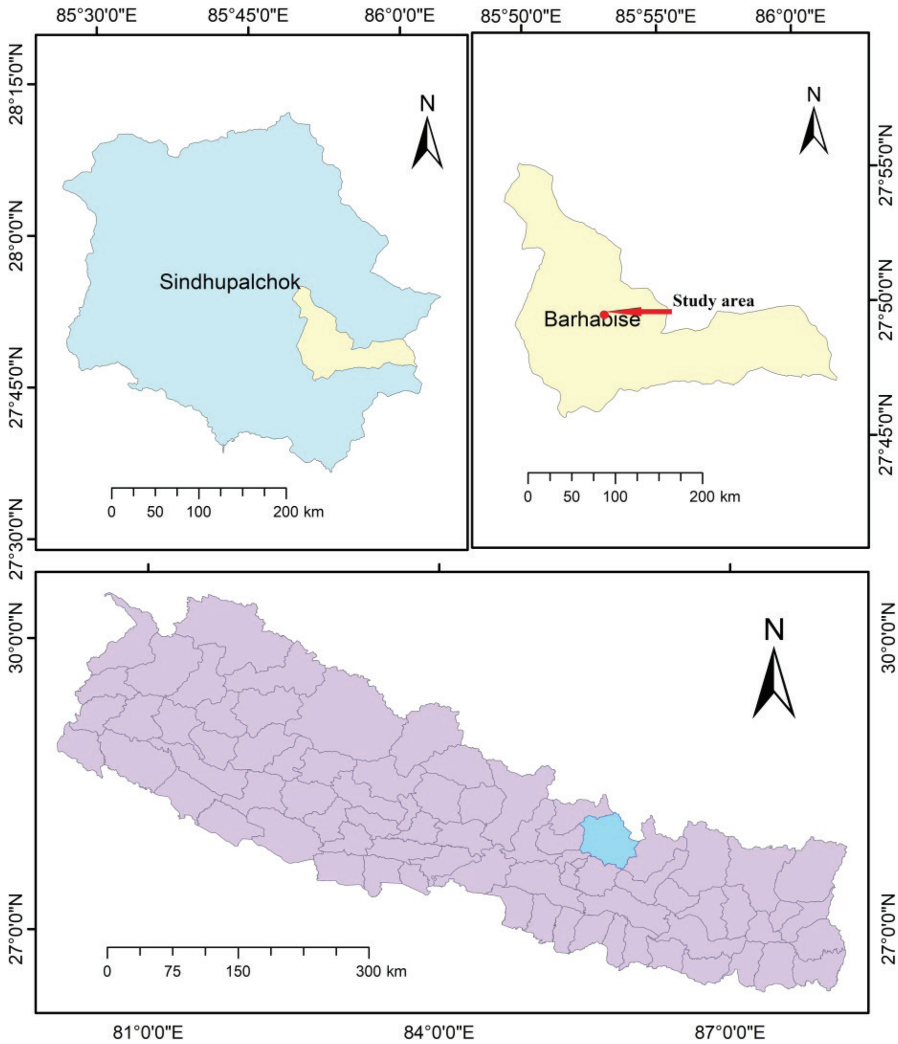

Fig. 1: Location map of the study area.

problems. Therefore, in this study, geological and engineering geological study, borehole log analysis, instrumentation data analysis, and numerical modeling of the slope using FEM based on the geotechnical data were done to trace out the root of the problem.

METHODOLOGY

The rock slope deformation analysis was investigated in the deformed slope (Fig. 2) using kinematic analysis, inclinometer as well as numerical modeling. The field study, a 1: 50000 scale topographic map, a geological map by Stöcklin and Bhattarai (1977), as well as an engineering geological map by the Middle Bhotekoshi Hydroelectric Project were all used to define the deformation characteristics and analysis. The study area is located in the intercalation of the psammitic schist and pelitic schist in the ratio of 4:1 ratio that was determined by the geological study. Stöcklin and Bhattarai (1977) named this formation the Kunchha Formation which has grey-green gritty phyllite and metasandstone, however, the phyllite is metamorphosed into schist in the study area.

After the geological study, the geotechnical study was followed by core logging of the borehole where the inclinometer was placed to determine the rock deformation movement. During the core logging, Rock Quality Designation (RQD) of the core was measured according to the method developed by Deere et. al. (1989) and Palmstrom (1982). Similarly, according to Bieniawski (1976; 1989), Barton and Choubey (1977), Hoek (1997), and Hoek et. al. (1995), the geo-mechanical classification of rock mass, Joint Roughness Coefficient (JRC), Geological Strength Index (GSI) of the rock mass in the cut slope were measured. The field investigation and core logging data are associated with the geotechnical investigation, which were used to observe the nature of discontinuities (foliation, joints set, quartz vein, etc.), aspect ratio of pelitic, and psammitic schist and deformation beneath the surface.

Furthermore, the inclinometer data was measured by regular monitoring using the inclinometer 'GEOKON Model 6100' for monitoring the deformation displacement of the slope after the excavation. The slope movement records for more than one year were gathered monthly and were studied well. For numerical analysis of the slope was modeled in Phase2 8.0 (Rocscience – Phase2 v8.0) using 2D finite element modeling (FEM).

Fig. 2: Deformation area in cut-slope and secondary support application.

GEOLOGICAL STUDY

The study area belongs to the Lesser Himalayan Zone which is correlated with the Kunchha Formation of Nawakot Complex (Stöcklin and Bhattarai, 1977) and consists of metamorphosed shiny, green-grey to blue-grey phyllite. The type locality of the Kunchha Formation is composed of sericitic- chloritic green to grey, thinly bedded phyllites, gritty phyllites with thin intercalation of white quartzite, and amphibolites but metamorphic grade increase towards the major tectonic zones. That is the reason, from the study, the geology of cut-slope consists of pelitic schist and psammitic schist and the ratio of psammitic and pelitic schist is 4:1. Psammitic schist which is fine to medium-grained, laminated, sericitic- chloritic green to grey, and pelitic schist which is fine-grained, highly laminated, sericitic- chloritic green in color by field observation. Figure 3 represents the 3D diagram of the geology of the study area.

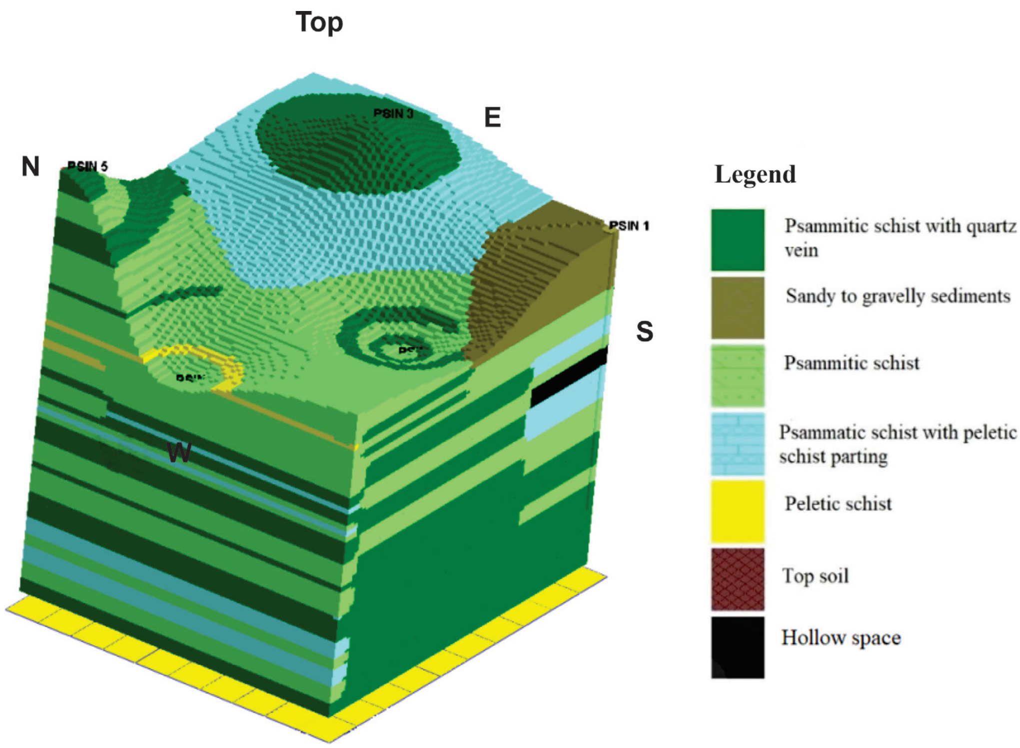

Fig. 3: Geological model of cut-slope area developed based on core logs.

CORE LOG STUDY

Altogether five boreholes were drilled to install inclinometers for monitoring. Before the excavation of the slope, the ground of the slopes was drilled for studying rock properties and discontinuities properties of below rock. During the installation time, core logging of the inclinometer installing holes was also carried out to study the sub-surface rock information (Fig. 4).

In the core study, quartz veins were densified layers that were developed during tectonic deformation in ductile conditions were distributed in several sections (Fig. 5). Close observation of the cores found that several sections have ductile-deformed schist but the information in the core log record was not mentioned. The distributions of the deformed quartz vein sections were distributed unevenly.

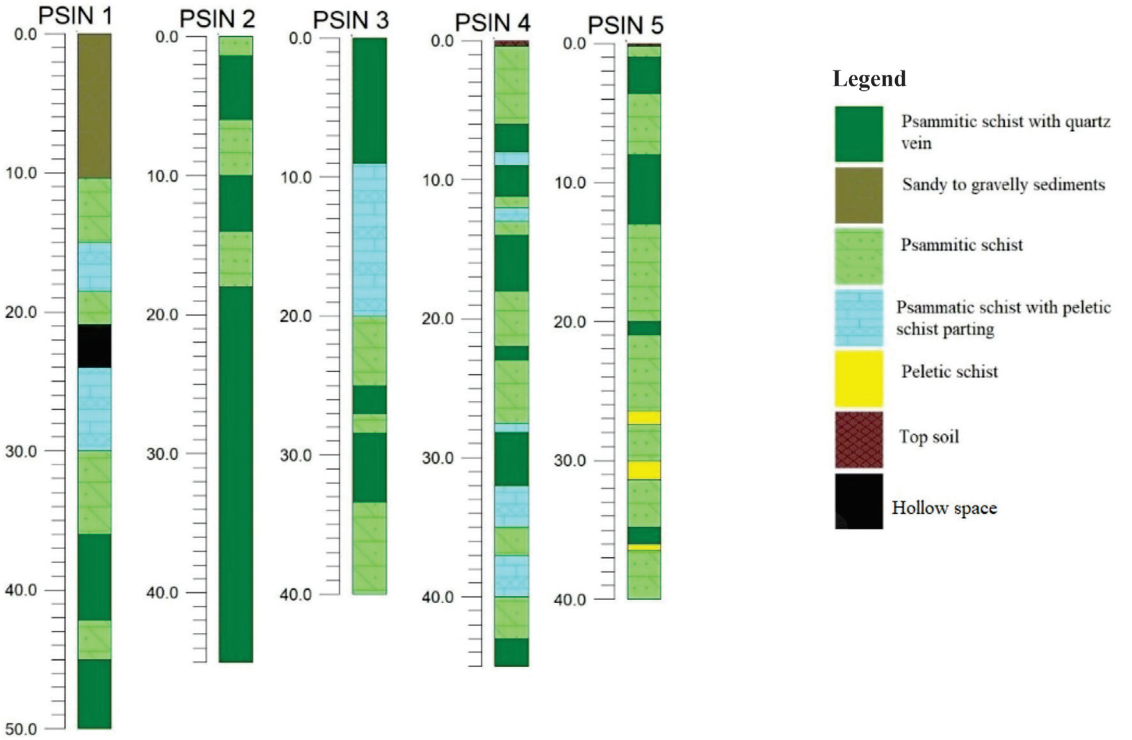

Fig. 4: Core logs of bores where inclinometers installed.

Fig. 5: View of core of the deformed section of PSIN-1.

GEOTECHNICAL STUDY

Five boreholes information were collected to see the discontinuity property of the ground. The other geotechnical data from the lab test of the slope material were gathered and presented in Table 1. Geo-mechanical characteristics of the rock were analyzed in outcrop and obtain data are given tabulated in the Table 2.

RQD is ranging from 54% to 80% using the volumetric joint count method. The Rock Mass Rating (RMR) was classified which shows the value of RMR in the range of 60 to 66 around the cut-slope area. This categorizes the rock mass of cut-slope area on Class II type, which is defined as the good quality rock. The UCS of the rock mass is calculated by using the Schmidt hammer. Besides the RMR, the GSI value of the rock was also determined. The GSI values of the slope were found from 55 to 65 which means the rock belongs to good rock.

Similarly, the rock has three sets of joints, and 3 to 4 sets were present in the section where the ductile deformed layer is present. The joint properties were also observed. From the field data, the value of the joint roughness coefficient ranges from 1.029 to 1.752, which indicates that the rock joints are slightly rough. Intact rock samples were tested in the laboratory and obtained are given in Table 2.

Table 1: Geo-mechanical data obtained from the different test.

Lithology		Specific Gravity	Moisture content saturation Dry condition	Bulk Density (kg/m^3)	Saturated condition
Weakly weathered schist	Max. value	3.06	1.02	2760	2770
	Min. value	2.7	0.34	2600	2600
	Standard value	2.74	0.56	2680	2690
Psammitic schist		2.75	0.4	2690	2710
Uniaxial compressive strength = 25.85MPa -35.76MPa					
Peak shear strength parameters				C=0.26-0.34Mpa	
	Φ=29.73-32.57Mpa				
Residual Shear strength parameters				Φ=19.12-20.76	
Elastic modulus = 5.16GPa - 6.23GPa					
Poisson ratio= 0.20					

Table 2 : Discontinuties parameters and calculated values.

Location	Uniaxial compressive Strength (MPa)	RQD	RMR	JRC	GSI
27º49’08.98”N	75	68			
85º52’47.47”E	(7)	(13)	60	1.029	60
946 m					
27º49’09.72”N	83	54			
85º.85”E	(7)	(13)	66	1.22	65
950 m					
27º49’09”N	88	74			
85º52’48”E	(7)	(13)	64	1.183	55
953 m					
27º49’07.37”N	91	80			
85º52’49.37”E	(7)	(17)	66	1.752	55
946 m					
27º49’06.69”N	66	67			
85º52’50.19”E	(7)	(13)	63	1.27	60
954 m					

Slope deformation data

Among five boreholes, only PSIN-1 borehole shown significant deformation in the cut-slope which can be seen in the depth-displacement trend graph with respect to time obtained by inclinometer data reading (Fig. 6). The graph shows both negative and positive displacements. The positive displacement can be related to the movement outside the slope surface, whereas, the negative displacement is related to the movement towards inside the slope. The zero value of displacement indicates that the slope has no deformation.

In the inclinometer data, at depth of 30 m to 35 m, the deformation (in mm) of the slope was observed. At the depth drastically movement of the slope was found. because from the core log data this zone lies in psammitic schist with pelitic schist parting and after that, there is psammitic schist only. So in psammitic schist deformation becomes low due to strength (UCS = 26 MPa). From 0 m to 32 m there may be a role of pore water pressure which increases deformation. In that zone, the joint is 3 to 4 sets which also plays role in deformation due to weakness made by joints in bedrocks.

Kinematic analysis

In the study area randomly, oriented structural data were collected and analyzed based on DIPS 6 software program. The facility is given by this software then a percentage of the possibility of failures was calculated. Analysis of discontinuity data and their relation to the slope face, taking the lateral limit is 20 and friction angle of the rocks is 30. Three modes of failure have been recognized which include plane failure (Fig. 7) wedge failure (Fig. 8) and direct topple (Fig. 9) that indicate probability of failure.

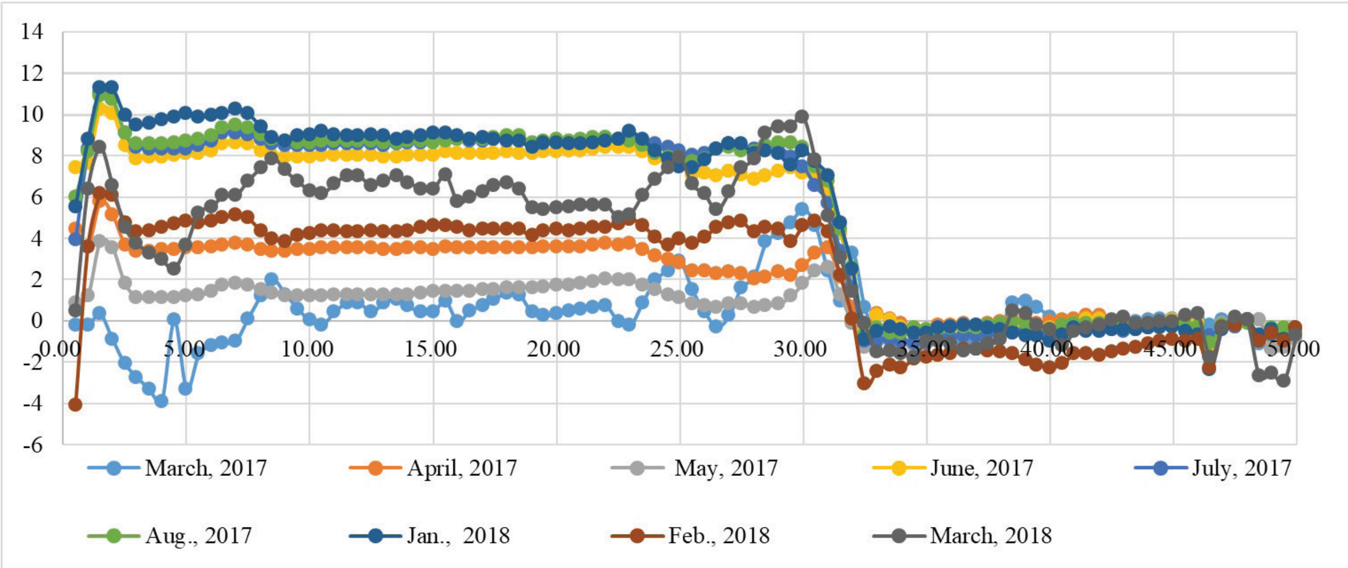

Fig. 6 : The graph of displacement with respect to depth of PSIN-1.

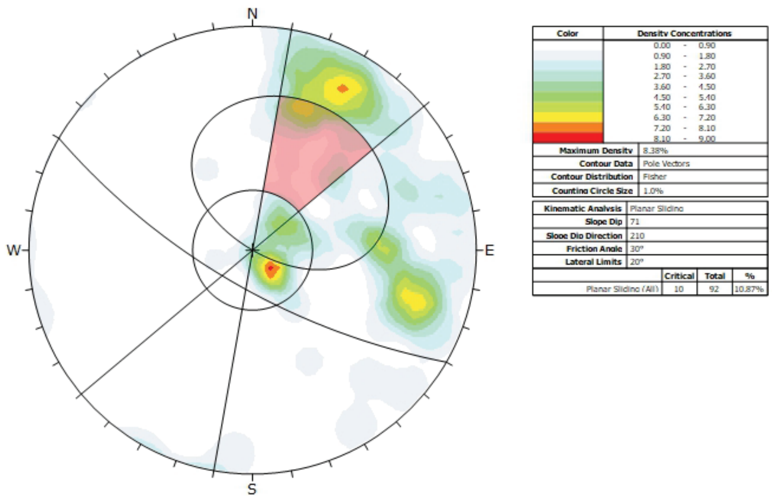

Fig. 7 : Analysis of plane failure at the cut-slope.

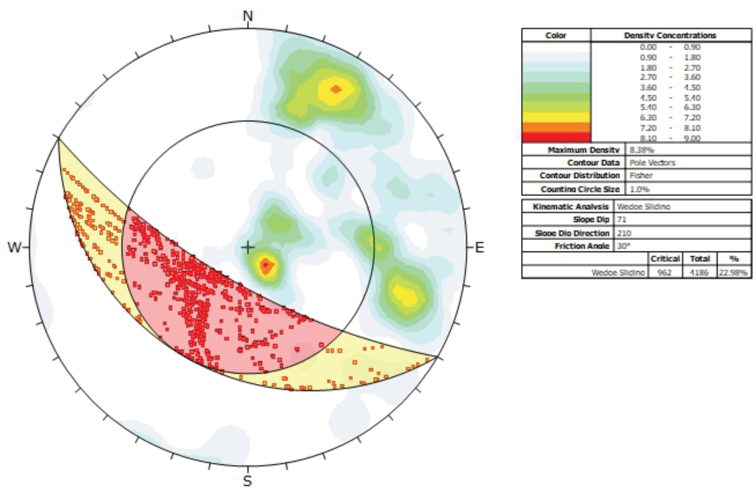

Fig. 8 : Analysis of wedge failure at the cut-slope.

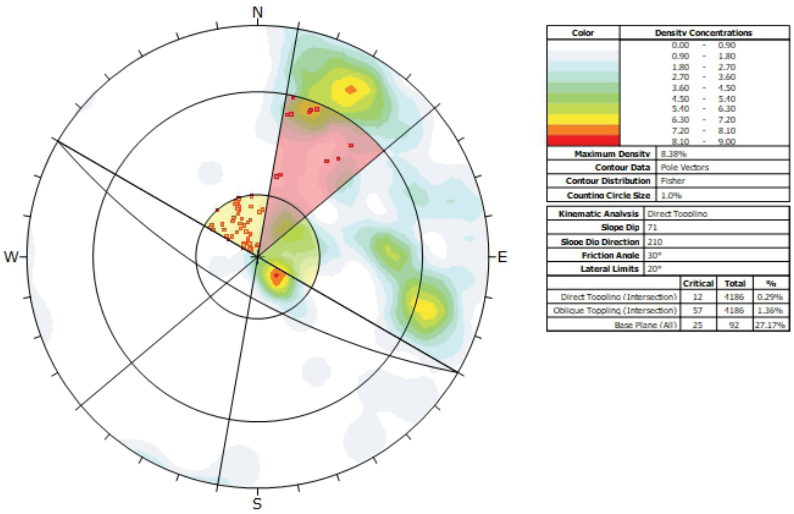

Fig. 9 : Analysis of direct toppling at the cut-slope.

Analysis by finite element method

The numerical modeling of the cut–slope was carried out by FEM in the RS2 program. The analysis was carried out according to the support condition that the project has applied. The project has used end anchored bolt and shotcrete with wire mesh to support the slope. The bolt properties and shotcrete properties were used as given by the project.

The total displacement, stress, and strain in the slope were analyzed and the result is presented. The effect of gravity loading was considered during modeling. The joints were modeled using the Barton-Bandis method where the material properties were computed using the generalized Hoek and Brown failure criteria. The graded type of mesh with three nodded triangles was used for meshing and the gradation factor value 0.1 was taken. Some assumptions were made during the study which is the effect of field stress was given by gravity only, the material property is isotopic and elastic so it is distributed equally throughout the model and the distribution of joints is paralleled deterministic.

In a 60 m high study cut-slope, the total displacement was analyzed and the result is presented in Figure 10. The steps indicate the benches that are present and the bolts are shown in the pattern. The numerical method has shown that the stress value of gravity loading is confined at 26-34 m depth of borehole as shown in Figure 10. The analysis has shown the maximum total displacement was 18 mm. The displacement of the slope is at a peak in the second slope beneath the peak where the deformation was around 14 mm. It decreases gradually while moving inward the slope and reaches zero in the vertical wall. The borehole of PSIN-1 is also shown in Figure 10.

Later, to avoid the displacement of slope that was incurred in the initial analysis and deformation record, the project used the rock bolt of length 10 m which helps to decrease the displacement of the cut-slope. The bolts were applied in a pattern with concrete blocks. The second support can be seen in Figure 2. During the study time, the project had not designed the second support, so the detailed analysis of the second support was not analyzed in this study.

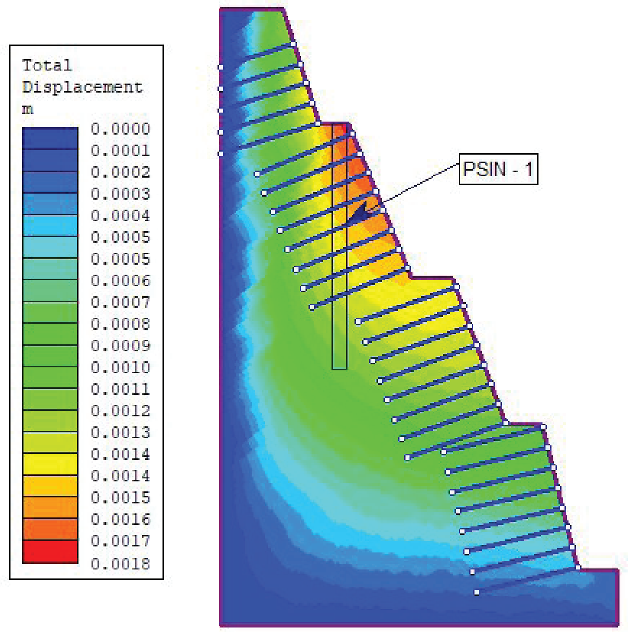

Fig. 10 : Deformation condition shown in FEM analysis of the cut slope at PSIN-1.

RESULT

The geotechnical data collected from the field in which rock mass class has shown that the rock of the slope is of good class but the joint condition of foliation set has a low JRC value. The rock strength parameter of intact rock shows the rock is moderate in strength but the rock mass strength is moderately weak. Similarly, the rock mass parameter also shows the rock mass of the slope belongs to the moderate at the upper part and weak at the below part. The core log shows that the joints in the slope are not so more but the presence of the foliation is more frequent. The quartz veins are more associated with the foliation plane in the ductile deformation section. The quartz veins spreading is unevenly distributed. The low roughness of the joints was obtained in the plane where quartz veins are dominant. From the geological study, there are two types of schists and the foliation is frequent in pelitic schist than psammitic schist. The rock mass class was good in RMR and GSI rock mass classification. The intact rock properties are fair to good but the joint strength along the foliation seems low.

The borehole log of PSIN-1 is located section shown displacement of the slope towards downward from the depth of around 30 m below. In this section, quartz veins were observed and a weak zone was developed due to several quartz veins aligned almost parallel to the foliation. The shear strength of the foliation along with such overburden seems critical for slope withstand. That was the reason why the slope has gone gradually displaced in the section. About 14 mm displacement was calculated at 28 to 31 m depth from numerical analysis. Displacement of 10–12 mm was recorded in the inclinometer which verified the numerical analysis information. This indicated that the quartz vein bearing weak layer which is almost parallel to the foliation was the main reason for the deformation.

The study of intact rock, major and minor joints of rock mass and its characteristics are challenging tasks because the stability of the designed slope is founded on the acquired data. While designing the present slope pieces of information were gathered and modeled for which deformation was encountered in some sections. The back analysis of the slope has shown that had the quartz vein bearing weak zone been considered during the investigation and designing, the deformation condition appeared now would have been addressed initially.

CONCLUSIONS

Deformation of cut slope at the powerhouse site of the Middle Bhotekoshi Hydroelectric Project was analyzed carefully to determine the causes of development of deformation. The slope has alternate layers of pelitic and psammitic schists with different thicknesses. Several quartz vein zones were present that are almost aligned parallel to foliation of schist. The cut slope was designed in good rock mass that has fair intact rock properties but weak joint properties. Foliation is the weakest joint which was aligned almost horizontal, slightly inclined towards cut slope direction. The presence of quartz veins had smoothened the joint condition which weakened the different foliation layers in the slope. The deformation occurred along the wreaked zone where the shear strength of the joint has a critical condition with overburden stress. In numerical analysis, it was around 28 to 31 m. In the borehole log of the area, a weak zone was also seen at the depth, and in monitored data shown the deformation was developed at depth 30 m which is corresponding with the condition.

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