Stability assessment of obliquely-bedded rock cuts using multi-prong procedures – case study

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Abstract. The stability of vertical cuts in rocky strata, associated with the provision of the transportation infrastructure through a mountainous terrain, is always a challenge for the geotechnical engineers. The problem becomes further complex if the cuts are parallel or near parallel to the bedding planes. Such a scenario results in all sorts of slope instability scenarios, including planar, wedge, rockfall, and toppling failure. A linear project was planned to pass through the mountainous stretches of western Saudi Arabia. The rock slopes exposed at the site after the excavations constitute igneous origin Granite/Granodiorite rock present in a moderately to highly weathered state and consist of two sets of discontinuities; one running almost parallel to slope faces and another nearly orthogonal to the major set of discontinuities. Based on the orientation of the discontinuities along the cuts on both the sides of the excavation, there is a high probability of all types of slope failures, including planar, wedge, toppling, or boulder/rockfall. This paper presents details of geologic field mapping, field and laboratory testing, and the software analysis of several modes of the possible slope failure modes. The study was carried out considering all the potential triggering factors, including rainfall, under both static and dynamic/seismic conditions. The paper also discusses the slope failure prevention measures recommended based on the interpretation of the field and laboratory data, software analysis, and the construction sequence.

1. Introduction

Rock slope instability is a common major geohazard for human activities in mountainous regions [1]. One of the major causes of slope failures encountered in such areas is the design of transportation systems without proper understanding of geological and geotechnical conditions of rock slopes [2-4]. Slope failures can lead not only to environmental deterioration and disruption of traffic for an unknown period but also to economic losses, injuries and/or fatalities [1,3-6]. This type of geohazards has been experienced throughout history when human or nature has disrupted the delicate balance of natural slopes. However, the increasing demand for man-made rock cuts and fill slopes for construction projects has been increasing the need to understand slope analysis methods as well as stabilization methods [7].

Predicting the stability of slopes is a classic problem for geotechnical engineers and is crucial when designing dams, roads, and tunnels [8]. This problem has been attracting the attention of many researchers [9-13].

A linear project was planned to pass through various mountainous stretches of Madinah province. Mountain cutting activity was required at this facility location having high peaks, steep slopes,
unstable boulders and discontinuities. Based on the reconnaissance survey, the rock slopes exposed at the site constitute igneous origin Granite/Granodiorite rock present in a moderately to highly weathered state and consist of two sets of discontinuities; one running almost parallel to slope faces and another nearly orthogonal to the major set of discontinuities. These two possible sets of discontinuities are shown in figure 1. There are high chances of collapse/slope stability failure during mountain cutting activity for facility installation which could endanger existing/future facilities and facilities in the vicinity of this location.

The main objective of this study was to carry out slope stability assessment of rock slopes considering applicable failure mechanism e.g plane, wedge, toppling or circular failures, and also possibility of rock falls. The study also aims at providing stabilization recommendations for the side slopes of the rock faces and overall stability of rock cut sections.

2. Field Investigations

Field investigations comprised of topographic survey, geologic survey, stereo net plots, surface sampling using block samples and subsurface sampling through boreholes. Details are provided in following sections.

2.1. Topographic Survey

Topographic survey of the study site was carried out using total station/DGPS and Drones. To visualize the terrain configuration, topographic data was used to plot 3-D digital terrain models using the SURFER software; 3-D model is shown in figure 2.

2.2. Geologic survey and stereonet plots

The geologic features recorded along two (02) vertical lines on south side and four (04) vertical lines on north side were dip and strike of all the discontinuities like cracks, fractures, and bedding planes. Also, type of rock forming these slopes and the infilling wherever present were also observed and recorded.

To visualize and analyze the relative position and intersection of the dip and strike of all the discontinuities with respect to each other and the rock slope face, geologic survey data along each line was plotted in 2-D and 3-D stereo net format. For the purpose, stereo net plotting facility available at app.visiblegeology.com/stereonetApp.html was used and typical stereonet plot is shown in figure 3. As most of our analysis is based on the performing kinematics, we have used equal angle projection stereonets. Since angular relationships and shapes are preserved, we can more accurately assess kinematic stability with an Equal Angle projection.

2.3. Surface and Subsurface sampling

Based on the data obtained from line geologic survey, a sampling plan was prepared to acquire the surface representative samples of the discontinuous rock and the infilling material wherever present in the discontinuities. In addition to the visual observation of the surfaces of the discontinuities, the samples were also required for the laboratory determination of the shear strength of these discontinuities. Three (3) locations were also selected to drill and sample the strata through boreholes. Boreholes were drilled using diamond and carbide bits to a depth of 20 m. Boreholes were executed using straight rotary drilling method.
Figure 1. Major set of discontinuities.

Figure 2. 3D digital terrain models of south side of the site.
3. Shear Strength Parameters
Surface block samples and samples retrieved from boreholes were examined in the field and then tested in the laboratory for unconfined compression test, point load test of rock and direct/interface shear tests as per relevant ASTM standards.

To obtain the lowest shear strength along the discontinuities simulating the near surface strata, the direct shear tests were performed at low normal loading stress of 25, 50, and 75 kPa. To simulate saturated conditions, the tests were repeated by flooding the specimens with water before the conductance of the test. The lower and upper limits of shear strength parameters through direct shear test are summarized in table 1. For the upper limit parameters, the tests were conducted on the specimens under in-situ conditions. On the other hand, for the lower limit parameters, the test specimens in the direct shear box were filled with water and sufficient time was allowed till the material in the discontinuity gets saturated. The upper and lower limit parameters for toppling mode of failure were assessed from the weathering extent of the rock prevailing in the entire rock mass. The maximum weathering extent determined from the information acquired from the boreholes and the geological mapping was used to calculate the lower limit parameters. Similarly, the minimum weathering extent was used to find out the upper limit parameters.

4. Rock slope structure
From the interpretation of the geologic data, it could be ascertained that the rock slope at the site constitute igneous origin Granite/Granodiorite rocks present in moderately to highly weathered state. The rock structure at most of the places consists of two set of discontinuities; one running almost parallel to slope faces and another nearly orthogonal to the major set of discontinuities (figure 1). The weathering of these discontinuities has resulted in the transformation of the rock structure into blocks of various sizes ranging from 1.0 to 5.0 m at most of the locations. The topographic and stereo net data were combined to generate cross-sections along the site. To visualize the slope configuration and the subsequent possible instabilities during and after the facility trench excavations, an excavation plan was also superimposed on these cross-sections. Few partially unstable boulders were also observed at
several positions on slopes of the site. The orientation of set of discontinuities with respect to the slope face angle does not seem to create unstable overhanging rock beds in toppling mode on north side. However, possibility of toppling mode is highly expected on south side of the mountain.

| Table 1. Shear Strength Parameters. |
|-------------------------------------|
| Toppling Mode | Sliding Mode |
| Angle of Internal Friction “$\phi$” | Cohesion “c” | Angle of Internal Friction “$\phi$” | Cohesion “c” |
| (Degree) | (kPa) | (Degree) | (kPa) |
| Lower Limit | 30 | 0 | Lower Limit | 35 | 150 |
| Upper Limit | 40 | 0 | Upper Limit | 42 | 250 |

5. Modes of slopes/rock failure
Based on the interpretation of the geologic and topographic data and the results of the field and laboratory investigations, possible modes of slope/rock failure were assessed for both north and south sides of the site as detailed below.

- Planar/wedge failure;
- Rock fall of the loose, unstable rock blocks at only few locations on the slopes;
- Toppling of the adverse set of discontinuities;
- Planar/wedge failure during the cutting of the slope toes during trench excavation especially along the steeper slopes.

The analysis of each of the above-mentioned slope instability scenarios was performed using the softwares from different sources.

6. Design Triggering Factors
Critical slope sections were marked based on the relative steepness, height and orientation of various set of discontinuities. All the critical sections were analyzed for the various possible failure modes under three different set of triggering conditions. In addition to the analysis using initial conditions, following scenarios are also considered for analysis:

- Possible saturation of the discontinuities due to rainfall and/or other flow conditions;
- Dynamic shaking due to the probable seismic event.

Roctopple and Rocfall from Rocscience Inc., USA and Planar Slide from the University of Alaska at Fairbanks were used respectively for the rock topple, rock fall, and planar slide failure analysis.

7. Results and conclusions
Details of various permutations of the analysis on different critical sections along both the sites are provided below.
7.1. Planar slide failure analysis

All critical sections were analyzed using the RocPlane software and factor of safety was generated for different conditions. A triangular distribution of hydraulic pressure was considered along the discontinuity. The results reveal a factor of safety of less than 1 in the case of 35% saturation and just above 1 in case of 0.1g earthquake acceleration conditions. The failed slope under saturated and earthquake acceleration triggering factors were reanalyzed with a target factor of safety (FOS) of 1.25 to find out the required rock anchorage force. The total anchorage force can be divided into an equivalent number of rock bolts to provide a minimum FOS of 1.25 against the worst slope instability triggering factors. Typical results at different sections are tabulated in table 2.

As discussed in the earlier sections, these upper and lower limits of parameters correspond to the maximum and minimum limits of the weathering extent of the rock prevailing in the rock mass. These are just representative of the localized factor of safety, the overall factor of safety controlling any mass discontinuity should fall somewhere in between the maximum and minimum limits.

| Analysis Condition            | Parameters   | Least FOS at Section C-C' | Least FOS at Section D-D' | Least FOS at L5 |
|------------------------------|--------------|---------------------------|---------------------------|-----------------|
| In-situ Conditions           | Lower Limit  | 0.87                      | 0.84                      | 1.102           |
| In-situ Conditions           | Upper Limit  | 1.23                      | 1.21                      | 1.785           |
| 35% Saturation Level         | Upper Limit  | 0.93                      | 0.93                      | 0.298           |
| 0.10g Seismic Acceleration   | Upper Limit  | 1.05                      | 1.05                      | 0.907           |
| Anchor Bolts                 | Upper Limit  | 1.25                      | 1.25                      | 1.250           |

7.2. Rock/Boulder Fall Analysis

Rock fall scenario for the most critical section of the site was configured in RocFall software. The boulder was placed at the probable location and its fall projectiles and hit points were measured. The selection of parameters for the rockfall analysis was based on the back-calculation of the several rock fall scenarios observed in the area. As revealed from the results, the boulders would probably be hitting the facility location and then bounce to other points on the access road. To prevent this unsafe situation, a barrier was simulated at 2.0 m away from the edge of facility. The rock fall simulations were repeated with the barrier in position, and as per the total hits, boulders have high probability of hitting the wall to maximum height of 2.0 m.

7.3. Rock Toppling Failure Analysis

For analysis purpose, rock topple failure was performed at critical sections. A triangular distribution of hydraulic pressure was considered along the discontinuity. FOS against toppling or base sliding was measured against different conditions for each of the slope configuration. As FOS for 25% saturation conditions and 0.1g earthquake conditions have been found to be less than 1, rock bolts option of the software was considered to stabilize the slopes. A minimum FOS of 1.25 was considered as the target.

As discussed in previous sections, the overall factor of safety controlling any mass discontinuity should fall somewhere in between the upper and lower limits of parameters. A FOS of less than 1 for in-situ conditions represent localized conditions which does not control and therefore is not prevailing in the overall rock mass.
Table 3. Summary of Least FOS against toppling failure.

| Analysis Condition                        | Parameters    | Least FOS |
|-------------------------------------------|---------------|-----------|
| In-Situ Conditions                        | Lower Limit   | 0.61      |
| In-Situ Conditions                        | Upper Limit   | 1.07      |
| 25% Saturation Level                      | Upper Limit   | 0.88      |
| 0.10g Seismic Acceleration                | Upper Limit   | 0.87      |
| Anchor Bolts (0.10g Acceleration)         | Lower Limit   | 1.51      |

8. Recommendations

Based on several possible slope instability modes, planar/wedge failure and the boulder fall failures from an orthogonal set of discontinuities set seem to be the most unfavourable circumstances on north side. On south side, slope toe cutting of the parallel set of discontinuities possibly during the trench excavation and the toppling and boulder fall failures from an orthogonal set of discontinuities set are the most critical scenarios.

Landslides case studies have always revealed that removal of the toe of the rock or soil slopes has always resulted in large landslides/slope failures. Based on the above premise and analysis results, the remedial measures for the critical conditions at the site are summarized below in table 4. In addition to specific remedial measures, shotcreting is also recommended to be used to arrest the existing potential unstable conditions and prevent the same in future by the ingress of surface and subsurface waters.

Table 4. Remedial Measures.

| Mode of Failure                                  | Solution                                                                 |
|-------------------------------------------------|--------------------------------------------------------------------------|
| Rock fall at some discrete locations on the slopes | A rigid toe wall of 2.0 m height along with removal of boulders/loose rocks |
| Planar/wedge failure                            | Four (04) rows of pressure grouted rock bolts normal to bedding planes along the north side, 100 kN each, 12 m long at 3.0 m grid spacing (3.0 m vertical and 3.0 m horizontal) |
| Toppling of the adverse set of discontinuities  | Four rows of rock bolts, 10 tons each, 12 m long at 3.0 m grid spacing (3.0 m vertical and 3.0 m horizontal) along the south side |
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