Stability assessment of rock slopes combining Slope Mass Rating and Qslope classification systems: A case study in Cerro San Eduardo (Guayaquil, Ecuador)

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Abstract. In the present study, the stability of the slope located in the Modesto Apolo Ramírez Avenue, is analyzed. The avenue is located prior to the access to the Cerro San Eduardo tunnel, which has had habitual problems of falling blocks to the roadway. For the study, empirical methodology was applied, including the data mapping based on geomechanical classifications such as Rock Mass Rating (RMR), Slope Mass Rating (SMR) and Q-Slope index, which assign a defined score, obtaining the quality of the rocky mass, and with this, the degree of stability of the slope. In addition, through the application of RocFall software, the empirical methodology has been compared with the analysis of rockfall trajectory, making a retrospective study of behavior and simulating the constant falling of blocks on the roadway.

As a consequence of the exploration, it was evident that the geomechanical classifications -in this particular case- are not completely effective to determine the degree of stability of the massif. This is due to the fact that, even though the slopes are globally stable, these classifications do not seem to adequately determine a level of risk against rockfalls, as can be seen from visu. Therefore, it can be seen that the slope does not have a risk of collapse, but instead presents a high danger of landslides that could cause considerable economic and human lives losses. The study recommends geometric solutions for impact mitigation to prevent future damage.

Keywords- RMR, SMR, Q-Slope, stability, massif, impact.

1. Introduction

Given the population growth of the city of Guayaquil, there is a need for roads that communicate certain populated areas, which is the case of the Modesto Apolo Ramírez Avenue. The avenue has a slope located on the right side, prior the entrance of the tunnel San Eduardo in the north-south direction, where the hill of the same name is located. This hill has an exposed slope of considerable height, with a limestone - diacastic lithology and presence of fragments of clay and silty rocks, which leads to constant slides of exposed blocks. This generates a situation of risk for the users of the road and urges the present stability analysis.
In the present research, geomechanical classifications RMR, SMR, and Q-slope were used to determine the stability of the rock masses. In addition, the application of empirical methods is contrasted to slopes with an analysis by falling blocks. This comparison strengthens the current approaches and recommendations that suggest the application of empirical methods as a starting point for outlining a problem of instability. So, they allowed directing the study in such a way that it reaches the ideal solution by means of analytical or numerical methods [1].

2. Geological setting
The study area is situated southwest of the city of Guayaquil, at Km 14.5 of the coast road, on the sides of Modesto Apolo Ramírez Avenue, which was built as a bypass to the San Eduardo tunnel. The zone of interest corresponds to the Cayo and the Guayaquil Member formations. Both formations of Senonian and Maestrichtian age ([2],[3], [4]) of the Cretaceous superior to the Eocene, with wide sequences and thin stratifications with dipping predominantly towards the south. [5]. The area of study is shown in Fig. 1.

![Figure 1. Orthophoto of the study area.](image)

![Figure 2. Location map of the study area with the characteristic geological formation. Modified from Instituto Geográfico Militar [5].](image)

3. Field work and results
3.1. Geomechanical stations and previous kinematic analysis
We map the outcrop by 4 geomechanical stations, divided by the significant change of structural domains in each zone. For each one of them, the information of a profile, dipping and diving direction of the main families of discontinuities was collected. In this way, with the input of the data collected in the Dips 6.0 software, it was possible to obtain stereographic projections with the concentrations of poles according to each station and to group them in families. By cinematically analyzing each part of the slope, the possible types of faults that could occur in each sector were made evident.
For the kinematic breakage analysis, geotechnical parameters of hard shales were considered. Since there is no data on friction angle or specific weight of the rock, these values are assumed according to Hoek and Bray [6], which establish a range of 25-35° for the friction angle in the case of soft sedimentary rocks. It was assumed an intermediate value of 30°, which stands for sandstones, shales, and siltstones. This value will be used as a friction circle in the kinematic model. In Fig. 3, are presented the stereographic projection where details the specific breakage for each station.

The kinematic analysis requires the preliminary knowledge of type of failure established a priori (SMR) and knowing whether the structure is stable or not (Q-Slope).

**Figure 3.** Diagram of pole density and breakage typologies. (a) location of the geotechnical stations (EG in Spanish “Estación Geomecánica”) on the orthophotography; (b) EG3 Instability due to planar sliding type failure; (c) EG4 Instability due to wedge type failure; (d) EG2 instability due to flexural toppling. Modified on: Dips 6.0 program.
As can be seen on the field, in the EG1 and EG4 stations the most visually evident type of instability is the wedge, this statement is verified with the kinematic analysis performed (figure 3c). Nevertheless, in the EG4 the wedge does not form within the zone of kinematic instability given that the structural domain of the mapped zone differs from that of the upper part of the slope where the discontinuities are clearly defined. The GS-2 and GS-3 stations present a different type of breakage from the wedge: it is a failure due to toppling in EG2, a failure due to planar sliding in EG3, and it is also observed that in certain sectors of the latter stations there is a greater presence of falling blocks apparently produced by the instability of the faces of the slope (figure 3b and 3d).

### 3.2. Results of Methods used

Once the families of discontinuities and the types of instabilities or ruptures most likely to occur in each station have been obtained, the slope is evaluated using the empirical methods described above (table 1, table 2).

**RMR:** To determine the SMR, it was necessary to previously calculate the basic RMR of each station.

It was possible to find out that in general, all the slopes presented a class of rock Type III, which corresponds to an average quality. This matched with the field experience, as sectors with intact rock were found and resistances that ascended up to 68 MPa were evidenced, considered an acceptable value within the geotechnical characteristics of a sedimentary formation.

| Geomechanical Stations | Height of the slope | RMR-1 Simple compr. strength | RMR-2 RQD | RMR-3 Spaced Diaclas | RMR-4 Water | RMR basic | Quality of the rock |
|------------------------|---------------------|----------------------------|-----------|---------------------|------------|-------------------|---------------------|
| GS-1                   | 12                  | 4                          | 8         | 8                   | 14         | 15                | 49                  | Type III*           |
| GS-2                   | 23                  | 7                          | 8         | 8                   | 11         | 15                | 49                  | Type III            |
| GS-3                   | 19                  | 4                          | 8         | 8                   | 15         | 15                | 50                  | Type III            |
| GS-4                   | 15                  | 4                          | 8         | 8                   | 15         | 10                | 45                  | Type III            |

*Type III= Medium

**SMR and Q-Slope:** Whenever the basic RMR of each station is obtained, the SMR is calculated. Once the SMR value is obtained and considering that the mechanism of breakage has been determined a priori (previous kinematic analysis), the classification results suggest that all the studied areas obey to a “Class III – Partially stable” category, except the EG3 that evidences a stability "Class IV- Bad", as detailed in table 2.

These categories suggest for "Class III", that the slope responds to normal quality with partial stability; its probability of breakage would be triggered by some joints or many wedges and the type of treatment to be received to avoid damage would be systematic. Whereas the "Class IV" specifies that the slope is unstable with the presence of several joints and requires mandatory correction.

It is presumed that this classification does not precisely define the situation analyzed as the methodology does not consider the falling blocks. The Q-slope system (table 2) was also applied, which indicates:

a) The slope at stations 1, 2 and 3, is within the stable limits, as shown in figure 3. Therefore, no correction measures are required on the frontal side of the slope, according to each zone analyzed.

b) Sector 4 presents partial stability, and it is situated at the limit towards the zone of uncertain stability (figure 4). However, considering that the location of the uncertainty is oriented towards the stable zone, it is determined that the slope does not require greater correction in its dip angle either.
Figure 4. Presentation of the stability of the slopes of each geomechanical station. Modified on: Bar and Barton [7].

Table 2: Results of SMR and Q-slope systems for the Cerro San Eduardo - Guayaquil slope stations.

| Geomechanical Stations | SMR | Q-slope (Jwice=0.65 ∧ SRF=5) | Rock stability | RQD | Jn  | Qslope | β     | Slope stability |
|------------------------|-----|-----------------------------|----------------|-----|-----|--------|-------|----------------|
| GS-1                   | 0.15| 1  -60  50                 | Class II       | 43  | 12  | 0.38   | 0.176 | Stable         |
| GS-2                   | 0.15| 1  -25  55.25              | Class II       | 41  | 12  | 0.09   | 0.042 | Stable         |
| GS-3                   | 0.7 | 0.7  -60  31               | Class IV       | 40  | 12  | 0.09   | 0.041 | Stable         |
| GS-4                   | 0.15| 1  -60  46                 | Class II       | 33  | 9   | 0.38   | 0.18  | Partially Stable |

Class II= Partially stable, Class IV= unstable

3.3. Rock Masses Detachment

When verifying that the different methods suggest that the slope is globally stable. Knowing this particularity, and high presence of falling rocks due to the important fragmentation, a rockfall analysis is performed with Rocfall software to determine the behavior and scope of the blocks detached from the slope and how much they could affect the surrounding area. Later, the general stability was also valued as the fall of successive blocks can cause a collapse of the slope due to the “domino effect”.

Class II= Partially stable, Class IV= unstable
Figure 5. Schematic trajectory of Block fall. Modified on: Rocfall.

For this purpose, during the field activities to collect information, blocks of varied sizes were observed. However, there is a large portion of small masses of about 0.3 kg. These blocks are separated from the massif apparently for inactivity. Still, the internal forces print a horizontal force which favors the falling blocks, estimated at 0.15 m/s [8].

Given the geometry of each profile, estimated from the topography and the use of a compass, there are different behaviors during the fall. A more critical situation is observed in profile 3, from figure 5. In this profile registered in Geomechanical Station EG3, a section is shown with a counter-slope in the cut, and as a consequence, the blocks acquire greater potential energy during the fall, which leads to greater height in the rebound. The modeling assumes 3 meters in height and 2 meters in length from the base of the slope to the roadway.

The fall of mass portions of the slope generates a threat to the circulation of the avenue. Therefore, with the objective of mitigating the risk, a containment barrier can be provided by knowing the trajectory that describes the movement of the blocks (see figure 6 and 7).
Figure 6. Retaining 100% of the blocks, which in their fall generate a maximum total energy of impact of 40 Jules (blocks falling directly to the barrier will have this energy). Also, due to the dissipation of energy in the rebound, it was observed that the greater amount of blocks represented only 10 Joules.

Figure 7. Retaining 100% of the sample. The total impact energy is approximately 38 Joules.

There are advantages and disadvantages involved in the decision to opt for one or another proposed location. If option 1, describe in figure 6 were considered, its benefit would lie in the ease of cleaning, since the rocks would be deposited at the level of the base, and the construction of the barrier with the technique of interest chosen by the designer, would be easier because of its perpendicularity to the ground. However, its design must be studied in detail, because if a total retention of the block is intended, the barrier would work mostly at 25% of its capacity.

On the other hand, if option 2 is considered, given the geometry observed in the graph on figure 7, it is more difficult to build and maintain. Although, it can be considered for cases in which the circulation area is adjacent to the foot of the slope.
4. Discussions and conclusions
To have road communication between the south and northeast of the city of Guayaquil, the San Eduardo tunnel was built in the sector known by the same name; For this construction of the access to the Modesto Apolo Ramírez Avenue was required, and implied cutting slopes due to the topography of the sector.

The steep slopes of the hill did not generate a threat at the time of the foundation, and as can be seen in the analysis proposed in this document (RMR, SMR and Q-Slope), It is a competent mass. However, in recent months there has been evidence of a large volume of blocks detaching from the solid mass and generate a risk for vehicles and passers-by that circulate on the avenue.

As a preventive measure, the local authorities have opted to divert vehicle traffic on a single lane, away from the area affected. Also, it was included the analysis of falling rocks and schematic solutions for retention barriers by Rocfall Software[8], which proposes an interesting modeling to predict the impact in distance and design a solution that enables the use of the road in its entirety.

This study analyzed the problems and causes of instability, but not the design of corrective measures. Even though, it was presented some geometric solutions. To design the complete reinforcement of the slope and analyze the different construction alternatives, it was necessary to perform the kinematic analysis of failure by wedge, overturning and planar breakage with the angle of friction of the site. Additionally, the study proposes the dimensions and geometric disposition of the barrier. Nevertheless, the appropriate technology should be sought, and aligned with a budget that makes implementation possible by optimizing resources thus, making it possible to transit without the current risk posed by the slope.

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