Slope Stability Analysis of a sector of San Cristobal Hills

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SUMMARY

Civil works require a geological risk study that can affect them. Depending on the situation, the studies to be carried out may be the rocky massif classification RMR and GSI and another, the slope stability analysis. This project aims to identify and locate the slopes unstable areas, which would lead to falling rocks in the event of an earthquake. With Dips software application, the stability analysis will be performed by the geometric method and with Rocplane and Swedge software will determine the safety factors and the treatment to stabilize them.
The results obtained indicate that the rock of some areas have a tendency toward planar rupture as in the case of station 1.

INTRODUCTION

This study is carried out because very near, at the slopes foot of part of San Cristóbal Hill, are located sports fields that would be affected by the falling rocks in the face of the earthquakes occurrence.

The methodologies for rock slope stability analysis are based on field assessments, mechanical exploration, seismic prospecting and interpretation, rock massif geomechanics classification, stability modeling using equilibrium limit analysis, SMR classification (Slope Mass Rating). In our case we did not perform mechanical exploration or seismic prospecting.

Field work was carried out, due to the geological and lithological characteristics, four structural domains were established and in these were located the geomechanical measurements station. The rocky massif geotechnical classification (RMR parameter -Rock Mass Rating- and GSI-Geological Strength Index-) will be made and then the areas of unstable slopes will be identified. In stations 1 and 2, biotytic granites emerge, at stations 3 and 4, horblendic granites, in stations 5 and 6, horblendic granodiorites and in stations 7 and 8, horblendic diorites quartz.

The fieldwork consisted in collecting discontinuities information as dip direction and dip, and their characteristics. With the information obtained, Dips software was used to determine the discontinuities families and later their possible failure was analyzed with the geometric method and specialized software.

Intrusive rocks are identified with qualitative petrological study in thin sections, using the polarizing light microscope. In turn, the rock matrix resistance was determined in the laboratory, and with discontinuities characteristics the RMR was determined and, indirectly, the cohesion and the friction angle, which favor or stop the failure, which will be simulated with Rocplane software.

Once the failures are established, recommendations will be made to maintain stability despite the danger detected and to be able to execute the work correctly, offering safety.

PRESENTATION OF THE PROBLEM

The project is located in Rímac district - Lima-Peru, between coordinates 8669300N-280000E, 8669300N-280300E and 8669700N-279900E, 8669700N-280200E
Metropolitan Lima has a high disastrous events occurrence rate in the historical or recent period by earthquakes as shown by the chronicles (IGP, 2005). For example, it is said that in the sixteenth, seventeenth, eighteenth, nineteenth and twentieth centuries, destructive earthquakes occurred that caused rocks to fall.

Figure 1. Project area location.

Geological description

This geomorphological unit corresponds to the Cordillera de los Andes' slopes and marginal ridges, formed by Batolito de la Costa's plutons and stocks: granodiorites, granites and quartz-diorites belonging to the Super Patap Unit with age between 75 and 92 Ma. There is also some dykes system with andesitic composition. In the Project area the highest peak corresponds to Cerro San Cristóbal.

The rocky massif is formed by rocks of color indexes from 10 to 40, holocrystalline panidiomorphic texture and bimodal, the crystals are medium to fine size, the alteration varies from fresh to moderately altered.

Colluvial soils have been observed (at the foot of the rocky outcrops slopes of intrusive origin, formed by blocks, boulders and angular gravels to subangles wrapped in a sand - silty matrix) and residuals (gravels, sands and fines that are covering the rocky outcrops).

In this area there are two characteristic reliefs: moderate to strong incline slopes (rocky mass) and smooth slopes cones.

In the project area, chemical weathering has slightly affected the rocky masses giving rise to residual soils and low potency colluvial soils. Small fallen blocks are observed due to the physical weathering, as well as blocks in the surface prone to fall before an earthquake, reason why the site is considered of average vulnerability, with mitigation activities could diminish the damages.

Discontinuities families that would originate planar types have been established.

Figure 2. Blocks located on the slope.

GENERAL OBJECTIVE

- Analyze the slope stability and recommend stabilization work.

SPECIFIC OBJECTIVES

- Geomechanically characterize the rocky massif to indirectly obtain parameters that will be useful for other purposes.
- Identify and locate possible slope faults occurrences.
- Give support recommendations based on existing software to stabilize them.

METHODOLOGY

Eight discontinuity measuring stations were established, establishing the existing families using the DIPS program, which are located in the respective geotechnical geological plane, with the following diaclases sets, having the following orientations:

N10º–30º	: Stations 1, 2, 3, 7 and 8
N70º–100º	: Stations 2
N80º–E-W	: Stations 6 and 7
N165º – 180º	: Stations 4

The same ones that correspond to the failure systems and Batolito de la Costa fracturing described by INGEMMET (2).

Also, a detailed characteristics description of the discontinuities was made, such as spacing, persistence, continuity, roughness, resistance of the walls, opening, filling, water leaks, which are detailed:

- Spacing: 0.10 cm 0.50 cm
- Persistence: 1.0 m to 10.0 m
- Continuity: Variable, from continuous to discontinuous
- Shape: Wavy, flat
- Roughness: Smooth and rough
- Alteration of walls: Fresh to slightly altered
- Aperture: Closed to slightly open
- Filling: Unfilled and with limes, rock and oxides fragments.
- Hydrogeological parameter: Dry

Rock matrix resistance determination

Nine samples were collected in the eight measurement stations, with punctual loading tests being performed, obtaining their compressive strength. A digital punctual loading device model VJT6752 (Figure 4), which is a small, portable hydraulic press equipped with "load cones" between which vertices are placed the rock and/or mineral specimens, or cubic samples or blocks subjecting them to compressive loads, until the sample rupture takes place.

Figure 3. Digital punctual loading test kit model VJT6752.

The "I_S" punctual load index is calculated, which is determined according to the procedure suggested by the International Society for Rock Mechanics (ISRM).

$$I_S = P / D^2 \text{ (Equation 1)}$$

where:
I_S = point load index (MPa)
P = Burst load (N)
D = Core diameter (mm) (50 mm)

<u>Sample kind and its equivalent diameter</u>

For other tokens sizes the index must be multiplied by the correction factor "F":

$$F = (D / 50)^{0.45} \text{ (Equation 2)}$$

And for other forms it is necessary to calculate the equivalent diameter "D_e" which is given by the following formula:

$$D_e^2 = 4 / \pi \, (W \times D) \text{ (Equation 3)}$$

where:
W = equivalent width where the load is applied

So:

$$\sigma c = 22 \, IS \, (50) \text{ (Equation 4)}$$

where σc represents the sample compressive strength.

The samples tested were small tabular pieces whereby the respective equivalent diameter was determined, and nine spot load tests were carried out, calculating their resistance, the location of these are shown in Table 1.

Geomecanic station	Samples	North coordinate	South coordinate
1	E1	8669600	279997
2	E2	8669593	280011
3	E3	8669622	280152
4	E4	8669576	280140
4A	E5	8669572	280125
5	E6	8669547	280094
6	E7	8669541	280126
7	E8	8669462	280231
8	E9	8669413	280240

Table 1. Samples location, spot loading tests

Figure 4. Medium grain biotitic granite (granular hipidiomorphic), incipient alteration (kaolin, sericite and chlorites).

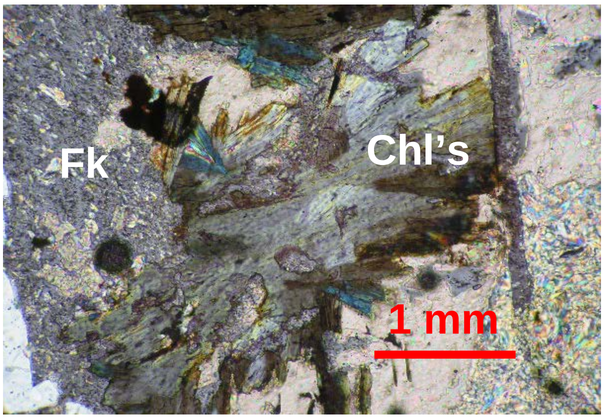

Figure 5. Biotitic granite with chlorites crystals by mafic minerals alteration, feldspars with moderate alteration transforming to kaolins and sericite. View on cross-bred niches.

Rocks were identified with Olympus Bx polarized light microscope.

Figure 6. Olympus Bx Polarized Light Microscope

RMR determination

Developed by Z. T. Bieniawski during the years 1972-73, and has been modified in 1976 and 1979, based on more than 300 real cases of tunnels, caverns, embankments and foundations.

To determine rock quality RMR index, use is made of six parameters of the terrain, which are listed below:

- Material resistance to simple compression
- RQD (Rock Quality Designation)
- Discontinuities spacing
- Discontinuities state
- Water presence
- Discontinuities orientation

RMR is obtained as a scores sum corresponding to the values of each of the six parameters listed (Table 2), these parameters are shown in the formats that are attached in Annex A2.

1	RESISTENCIA A LA ROCA SANA (MPa)	Ensayo carga puntual	> 10	4-10	2-4	1-2	-
		Compr. simple	> 250	100-250	50-100	25-50	5-25 1-5 < 1
	VALORACIÓN		15	12	7	4	2 1 0
2	RQD%		90-100	75-90	50-75	25-50	< 25
	VALORACIÓN		20	17	13	8	3
3	SEPARACIÓN DISCONTINUIDADES		> 2m	0.6-2	0.2-0.6m	0.06-0.2m	< 0.06m
	VALORACIÓN		20	15	10	8	5
4	ESTADO DIACLASAS		Muy rugosas Discontinuas Borde sano y duro	Ligeramente rugosas e < 1mm Borde duro	Ligeramente rugosas e < 1mm Bordes blandos	Rellenos e < 5mm Abiertas Continuas	Rellenos blandos e < 5mm Continuas
	VALORACIÓN		30	25	20	10	0
5	PRESENCIA DE AGUA	Caudal en 10m túnel	Nulo	< 10 l/min	10-25 l/min	25-125 l/min	> 125 l/min
		σ_w/σ_3	0	0-0.1	0.1-0.2	0.2-0.5	> 0.5
		Estado	Seco	Ligeram. húmedo	Húmedo	Goteando	Fluyendo
	VALORACIÓN		15	10	7	4	0

Table 2. Bieniawski's geomechanical classification (1979).

The RMR value ranges from 0 to 100, and the better the quality of the rock. Bieniawski distinguishes five types or rock classes according to the RMR value:

Calidad de macizos rocosos en relación al índice RMR

Clase	Calidad	Valoración RMR	Cohesión	Ángulo de rozamiento
I	Muy Buena	100-81	> 4 kg/cm²	> 45º
II	Buena	80-61	3-4 kg/cm²	35º-45º
III	Media	60-41	2-3 kg/cm²	25º-35º
IV	Mala	40-21	1-2 kg/cm²	15º-25º
V	Muy mala	< 20	< 1 kg/cm²	< 15º

Table 3. Rocky massifs quality (Bieniawski, 1979).

RESULTS

Rocky massif RMR classification with field harvested data

ESTACION 1 y 2

RMR			PUNTUACIÓN
RMR 1	RESISTENCIA A COMP. SIMPLE (kp/cm²)		12, 15
RMR 2+3	JUNTAS POR METRO		8, 13
			8, 10
		Media	28, 38
RMR 4	ESTADO DE LAS JUNTAS	Continuidad	2, 4
		Apertura	0, 6
		Rugosidad	3
		Relleno	6
		Meteorización	5
		Suma	16, 24
RMR 5	PRESENCIA DE AGUA		15
		SUMA TOTAL	59, 77

Table 4. Rock mass quality: Medium type III.

ESTACION 3 y 4

RMR			PUNTUACIÓN
RMR 1	RESISTENCIA A COMP. SIMPLE (kp/cm²)		12, 15
RMR 2+3	JUNTAS POR METRO		13, 17
			10, 15
		Media	35, 47
RMR 4	ESTADO DE LAS JUNTAS	Continuidad	2, 4
		Apertura	0, 6
		Rugosidad	5
		Relleno	6
		Meteorización	5
		Suma	18, 26
RMR 5	PRESENCIA DE AGUA		15
		SUMA TOTAL	68, 88

Table 5. Rock mass quality: Good type II.

ESTACION 5 y 6

RMR			PUNTUACIÓN
RMR 1	RESISTENCIA A COMP. SIMPLE (kp/cm²)		12, 15
RMR 2+3	JUNTAS POR METRO		8, 13
			8, 10
		Media	28, 38
RMR 4	ESTADO DE LAS JUNTAS	Continuidad	2, 4
		Apertura	1
		Rugosidad	5
		Relleno	1, 6
		Meteorización	5
		Suma	14, 21
RMR 5	PRESENCIA DE AGUA		15
		SUMA TOTAL	57, 74

Table 6. Rocky mass quality: Media type III.

The RMR geomechanical classification is Good to Medium; Type II to III.

GSI Index

Stations 1 and 2 vary from F / MB to F / B
Stations 3 and 4 vary from LF / MB to F / B
Stations 5 and 6 vary from F / MB to F / B

Stations 7 and 8 vary from LF / MB to F / B

It correlates with RMR classification.

Slopes stability analysis, Dips software application

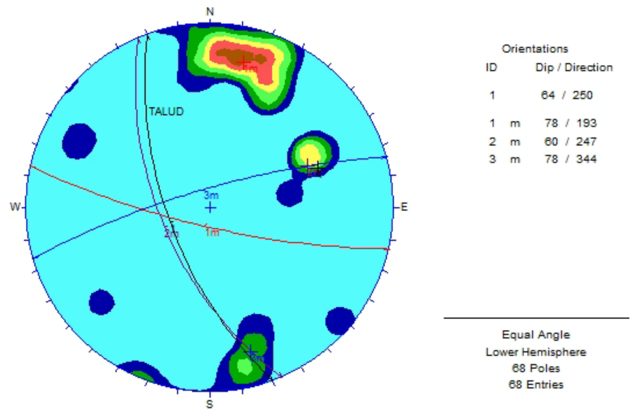

Figure 7. Geomechanical station E07, planar glide.

<u>Testing by geometric method</u>

Slope orientation and family 2 in the range of ± 20 °

Slope Bounding> Family Bounding> φ
64 °> 60 °> 35 °

The condition is met.

Applying Rocplane software

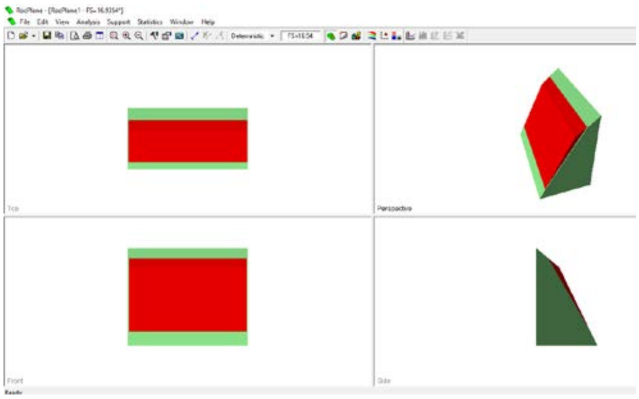

Figure 8. Slope 3D view with family forming the planar fault.

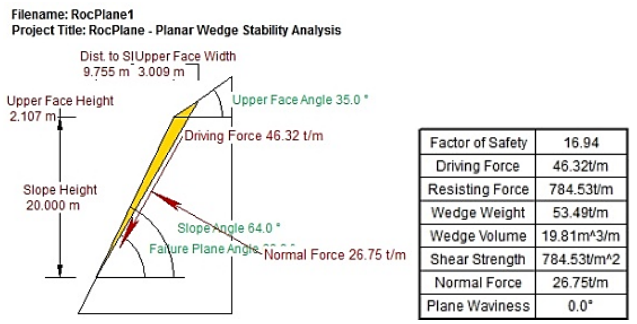

Figure 9. Slope 2D view with family forming the planar fault.

Safety factor is 16.9: <u>stable slope</u>

Considering only the slope angle and the family angle that causes the planar fault, the slope is not stable; with Rocplane software use the slope is stable, the difference is because in the first case only the orientation and the rock mass friction angle are considered, in the second case in addition to the orientations we consider the slope height and the parameters of cohesion and friction angle, obtained from the RMR.

Rocks resistance. Spot load tests

Intrusive igneous rock	Stations	Resistance to compression (σ_c) MPa
Biotytic granite	1 and 2	272.00 to 408.17
Horblendic granite	3 and 4	168.07 to 381.16
Horblendic granodiorite	5 and 6	236.20 to 458.94
Horblendic diorite quartz	7 and 8	277.69 to 462.46

Table 7: Intrusive rocks compressive strength values

The resistances variation is originated by rocks alteration, (sericite, clays, chlorites) identified in petroleum study.

CONCLUSIONS

- In the project area diverse intrusive igneous rocks appear; biotitic granite, horblendic granite, horblendic granodiorite and horblendic quartz diorite.
- The nine rock samples that were submitted to the point load tests have minerals sizes ranging from 2 mm to 5 mm, with an incipient alteration from fresh to slightly altered so that the resistance values have variations for the same rock type.
- With the discontinuities characteristics the rock RMR geomechanical classification was determined that is type II to III, good to medium rock, by the visual inspection, GSI was determined that correlates with the obtained RMR.
- DIPS software was used to determine the discontinuities families in the eight geomechanical stations. With this software was included the slopes orientation and stability analysis was carried out using geometric method. Rocplane software analyzed slope stability.

- Only the station E07 meets the geometric conditions for planar fault, using Rocplane software, was determined to be stable with FS (Safety Factor) of 16.9, the difference is explained because in the geometric analysis, only was considered the slope orientation and discontinuities family that originates planar fault, with the software, in addition to the respective orientations, it is considered the slope height of measurement zone as well as the natural slope height, the friction angle and the cohesion obtained in the RMR classification.

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