GEOTECHNICAL RISK ON UNSTABLE SLOPES OF THE PINNACLE PROPERTY

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Abstract

Peru, a country located in the Ring of Fire and among a variety of mountain ranges with diverse typologies of materials, which are exposed to geodynamic events either internally or externally.

Currently, the increase in population, which produces a demand for housing and roads, added to the lack of planning and organization at the time of urbanization are the main factors by which a risk is produced.

To face this situation, it's important to plan and implement methodologies that help to stratify the levels of geotechnical risk, vulnerability and geotechnical risk in order to optimize decision making for their reduction.

1 INTRODUCTION

1.1 Background

Geotechnical risk is understood as the probability or occurrence of an event that affects areas of population, structures or socio-economic activities.

In recent years, Peru has experienced an increase in population, which has led to the construction of new urban areas, as well as roads that will serve as connections for housing developments. This, in addition to the fact that Peru is a country located in the Ring of Fire and between a variety of mountain ranges which are affected by geodynamic events that occur externally and internally.

In 2017, the Directorate of Policies, Plans and Evaluation, DIPPE-INDECI, presented its "Seventh Virtual Statistical Bulletin of Reactive Management" (Table No. 01).

Table N° 01: Emergency chronological series according to phenomena.

Year	Phenomena	
	Slide	Rock Fall
2003	147	52
2004	101	19
2005	100	61
2006	161	160
2007	141	67
2008	170	68
2009	139	99
2010	126	78
2011	144	104
2012	151	59
2013	137	45
2014	185	69
2015	228	84
2016	64	39

From table N°01, the phenomena of landslides and rockfalls stand out, which, according to the period of time analyzed by the bulletin, present a constant increase according to time, this can be compared with the increase of population, which implies the construction of new urban areas and roads.

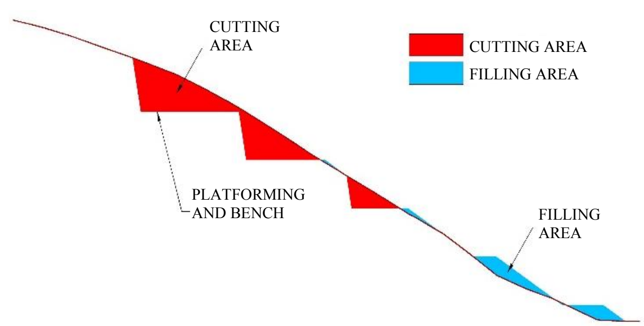
1.2 Study Area

To the south of Metropolitan Lima is located the district of Lurín, this district is characterized by its population increase achieved in recent years. The Lúcumo gully is located to the east of the district in mention, this gully hosts different properties, where the Pinnacle Property stands out with a total of approximately 1 245 ha.

Due to the immense extension of this property, several zones were identified as having unstable characteristics; however, there is an unstable area which stands out among the others, it is located approximately in the middle of the Pinnacle property. This area was delimited in 19 ha and in Picture N° 01 the satellite shot provided by Google Earth is shown.

It is important to point out that the Pinnacle property is destined to be an urban zone, for that reason it's expected the execution of 30° fill slopes and 80° cut slopes respect to the horizontal. In both cases height will be 12.00 m with 20.00 m benches (picture N° 02), this with the purpose of maximizing its developable areas.

Picture N° 01: 19 ha unstable area located in the Pinnacle Property.



Picture N° 02: Natural slope's cut and fill.

2 CHARACTERIZATION OF THE STUDY AREA

Gonzales de Vallejo (2002, p.622) "Geodynamic events that affect the earth's surface result in land movements of different lengths and characteristics that affect human lives, roads and urban areas, which constitute a geological risk"

The unstable zone contemplates along its extension external geodynamic events such as: landslides or falling rock blocks of different shapes and internal geodynamic events such as earthquakes, this because the district of Lurín is located in a area of high seismic probability.

The landslides or falling blocks are closely related to the climate of the area, because it is in a humid condition due to its proximity to the coast, this directly affects the properties of the materials.

2.1 Geomorphology

The unstable zone has slopes that on average are greater than 50% and most of its area presents debris cones generated by the accumulation of rock fragments mainly from the fragmentation of adjacent rocks, according to Bulletin N°43 of the Lurín Quadrangle (25-j) by Palacios (1992).

2.2 External Geodynamics

Through geological mapping it was possible to identify features corresponding to natural actions that may present a risk at the geotechnical level (Picture N° 03).

These features are caused by the site's particular geological conditions (adverse flat fractures, rock fractures, soil decomposition and others), by gravity and rainwater, which lubricate the rock mass fractures as explained by Duncan (2018, p. 393).

2.3 Geomechanics

Currently, the geomechanical classification of the rock mass is based on information recorded by geomechanical stations on the rock outcrops, which is why the global classification of the rock mass proposed by Bieniawski (1989) has been used.

According to Gonzales de Vallejo (2002, p.230) "Bieniawski's geomechanical characterization consists of the qualitative and quantitative measurement of the Uniaxial Strength of the rock structure, Degree of Fracture in terms of the Rock Quality Designation (Deere, 1953), Hydrological Conditions, Spacing, Conditions and Orientations of Discontinuities".

Picture N° 03: Note in the image the debris cones (middle to top)

From Bieniawski's classification others are derived such as the Geological Strength Index developed by Hoek and Brown (1997) which makes a quantitative evaluation of the rock mass and the Slope Mass Rating made by Romana (1993) which qualitatively and quantitatively classifies slope conditions by adjustment factors.

Table 02 summarizes the geomechanical evaluations of the unstable zone in question.

Table N° 02: Geomechanical evaluations of the unstable zone.

Sector	Unstable (10 Ha)		Status
Rock Mass Rating (RMR)	44	45	Very good rock
Slope Mass Rating (SMR)	59	60	Partially stable slope with some wedged discontinuities.

2.4 Geotechnical Parameters

In every geotechnical project, altered samples are obtained (by excavating pits) and unaltered samples (by drilling) which must be analyzed in a certified laboratory following the standards of the American Society for Testing and Materials (ASTM).

The tests conducted in the unstable zone are presented in the following table:

Table N° 03: Laboratory testing.

Test	ASTM
Soil particles gradation	D-422
Atterberg Limits	D-4318
Water Content	D-2216

Test	ASTM
Unified Soil Classification System (USCS)	D-2487
Direct Shear Test (Soils)	D-3080
Point Load Test	D-5731
Soil Density	D-2937
Direct Shear (Rock)	D-5607

All the tests conducted are valid for the unstable zone (19 Ha), however, the results obtained were compared with the existing bibliography for the case of soils and with empirical correlations for the case of rocks (Bieniawski Methodology, Hoek and Brown Methodology through RocData 3.0 software), in order to obtain a range of values and thus consider an optimal value for the development of the geotechnical model. The results are presented in tables N°04 and N°05

Table N° 04: Geotechnical Parameters – Soil.

Material	C (kg/cm2)	Ø (°)	γ (Tn/m3)
Alluvial Deposit	0.009	27.40	1.60
Colluvial Deposit	0.020	25.00	1.90
Residual Deposit	0.016	28.00	1.70

Table N° 05: Geotechnical Parameters – Rock.

Zone	C (Mpa)	Ø (°)	Considered C (Mpa)	Considered Ø (°)	γ (Tn/m^3)
Unstable	0.220 a 0.275	27.00 a 54.81	0.27	35	2.56

2.5 Seismic Coefficient

According to Suarez (2009) "Vertical accelerations have received less attention than horizontal ones, because their effect on structures and slopes is lower", this can be understood in a simplified way as the behavior of the soil in compression is relatively good, but not in traction.

Hynes, Griffin and Franklin (1983) suggest that for the case of pseudo static analysis on slopes, a seismic coefficient equal to half the peak ground acceleration (PGA) should be considered.

The Peruvian regulation E030 "Seismic Resistant Design" zones Peru in four zones to which a value of seismic acceleration is attributed. The unstable zone in question is located in the zone with the highest value where it is attributed an acceleration of 0.45 gal or cm/s2.

3 STABILITY ANALYSIS

Stability analyses were evaluated in order to obtain ranges and quantify the geotechnical hazard, these analyses were focused on the following points:

3.1 Stability by Discontinuities

The evaluation of stability analysis by discontinuities is based on data from the families of discontinuities of the rock mass which were determined in the field, in conjunction with the geomechanical stations.

The stereographic representation was made by means of DIPS 6.0 software, where different types of failure can be identified such as: planar, wedge or toppling. (Table N° 06).

Table N° 06: Types of failure according to discontinuity evaluation.

Zone	Discontinuities Family	Discontinuities Dip	Discontinuities Dip Dir.	Slope Dip	Slope Dip Dir.	Type of Failure Before shear	Type of Failure After shear
Unstable	F1	61	11	41	349	N/A	Planar
	F2	68	34			N/A	Wedge
	F3	46	191			N/A	Toppling

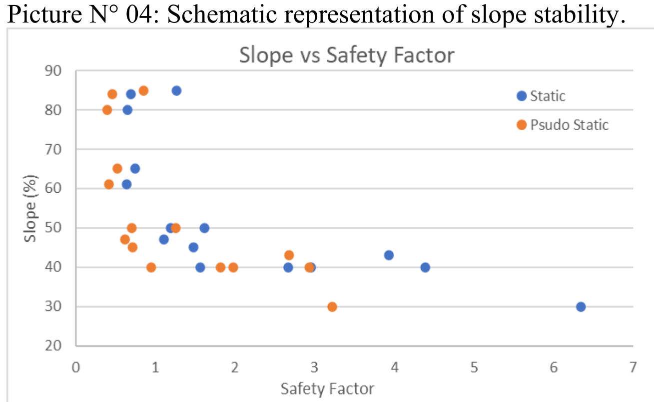
3.2 Slope Stability

The stability analysis evaluation is conducted by using the infinite slope system since it is based on straight fault surfaces, i.e. parallel to the ground surface.

With this system you can determine the safety factor in slopes which depends on the slope geometry, geological, geotechnical and seismic parameters.

The stability analyses were made using Rocscience's Slide 6.0 software and all the analyses are summarized in (Picture N° 04)

Picture N° 04: Schematic representation of slope stability.



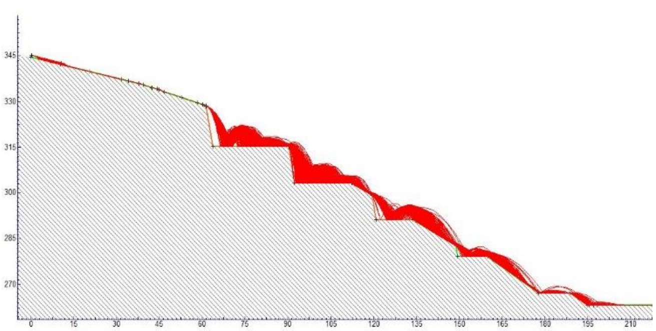
3.3 Rock Block Slide Simulation

Since a rock block, at the time of release from a slope can have a number of possible trajectories, Jones (2000) mentions that the trajectories depend on parameters are the slope geometry, the slope surface type and the rock block geometry.

Table N° 07: Parameters which determine the fall path.

Factor	Parameter
Slope Geometry	Gradient, Length
Slope Properties	Coefficient of Restitution
Rock Geometry	Size and Shape

Through geological mapping, block sizes were identified in the range of 0.50 m to 3.00 m. Rock block fall simulations were performed using Rocscience's RocFall software (Picture N° 05).



Picture N° 05: Rock block fall simulation for the natural slope.

4 GEOTECHNICAL RISK MATRIX

In 1980, Saaty developed the Analytical Hierarchy Process (AHP) which consists of formalizing the understanding of a multi-criteria problem through a hierarchical model, which allows the operator to structure the problem visually.

The AHP tries to break down a problem and then join all the solutions of the sub-problems in one conclusion.

Toskano (2005) mentions, the AHP allows efficiently and graphically organize information about a problem, break it down and analyze it in parts, visualize the effects of changes in levels and synthesize. The AHP is based on:

- Hierarchical model structuring (problem representation).
- Element prioritization.
- Binary comparisons between the elements (Table N° 08)
- Evaluation of the elements by assigning weights.
- Synthesis.
- Sensitivity analysis.

AHP as a tool has been applied in several countries to incorporate the preferences of operators involved in a decision-making conflict.

Because binary comparisons are a necessary basis, the AHP uses a rating scale with scores ranging from 1 to 9 to rate the relative preferences of the elements being compared.

Table N° 08: Saaty's verbal scale (1980) adapted by CENEPRED (2015)

Score	Elements in comparison
9	Absolutely more important than…
7	Much more important than…
5	More important than…
3	Slightly more important than…
1	Equally to…
1/3	Slightly less important than…
1/5	Less important than…
1/7	Much less important than…
1/9	Absolutely less important than…

4.1 Geotechnical Hazard Matrix

The geotechnical hazard matrix was developed through Saaty's (1980) hierarchical analysis process, which started with the geodynamic agents that would create a geotechnical hazard. Four parameters were defined, which are described below:

The first parameter, which involves the morphology and stability analysis of the slopes which were stratified according to their safety factors in accordance with regulations.

The second parameter involves the geomechanical characterization of the area, where the RMR and SMR assessment of the slopes is stratified.

The third classified parameter is conditioned to the fall diameters, where the diameters of blocks already detached from the slopes are classified.

The last parameter involves an internal geodynamic event, where it is classified based on the seismic zoning of the E030 standard "Seismic Resistant Design", the Mercalli intensity or the Richter scale.

The parameters mentioned with their respective descriptors are presented in the following tables:

Table N° 09: Hazard descriptors, for slope and SF of slopes.

Parameter		Slope and Slope SF	Weight	0.312
Descriptors	S1	Slope > 60% FS $_{static}$ < 0.75 FS $_{seismic}$ < 0.50	PS1	0.416
	S2	Slope 30 to 60% FS $_{static}$ < 1.50 FS $_{seismic}$ < 1.25	PS2	0.262
	S3	Slope 12 to 30% FS $_{static}$ < 2.00 FS $_{seismic}$ < 1.50	PS3	0.161
	S4	Slope 3 to 12 % FS $_{static}$ > 2.00 FS $_{seismic}$ >1.50	PS4	0.099
	S5	Slope < 3 % FS $_{static}$, FS $_{seismic}$ with high valuation	PS5	0.062

Table N° 10: Hazard Descriptors, for geomechanical valuation of RMR and SMR.

Parameter		SMR and RMR valuation	Weight	0.280
Descriptors	S1	0 to 20	PS1	0.416
	S2	20 to 40	PS2	0.262
	S3	40 to 60	PS3	0.161
	S4	60 to 80	PS4	0.099
	S5	80 to 100	PS5	0.062

Table N° 11: Hazard descriptors, for diameters of rock blocks slides.

Parameter		Rock block diameter	Peso	0.128
Descriptors	S1	D > 3.00 m	PS1	0.416
	S2	2.00 m < D < 3.00 m	PS2	0.262
	S3	1.00 m < D < 2.00 m	PS3	0.161
	S4	0.50 m < D < 1.00 m	PS4	0.099
	S5	D < 0.50 m	PS5	0.062

Table N° 12: hazard descriptors, for the zone's seismic acceleration.

Parameter		Seismic acceleration	Weight	0.280
Descriptors	S1	a $_{seismic}$ > 0.45 g M $_{Mercalli}$ = XI a XII M $_{Richter}$ > 8.0	PS1	0.416
	S2	0.35 g < a$_{seismic}$ > 0.45 g M $_{Mercalli}$ = IX a X M $_{Richter}$ > 6.0	PS2	0.262
	S3	0.25 g < a $_{seismic}$ > 0.35 g M $_{Mercalli}$ = VI a VIII M $_{Richter}$ > 4.5	PS3	0.161
	S4	0.10 < a $_{seismic}$ > 0.25 g M $_{Mercalli}$ = III a V M $_{Richter}$ > 3.5	PS4	0.099
	S5	a $_{seismic}$ < 0.10 g M $_{Mercalli}$ = XI a XII M $_{Richter}$ > 8.0	PS5	0.062

Table N° 13: Hazard Matrix

Very High Hazard	**0.262 ≤ R < 0.416**
High Hazard	**0.161 ≤ R < 0.262**
Medium Hazard	**0.099 ≤ R < 0.161**
Low Hazard	**0.062 ≤ R < 0.099**

5 VULNERABILITY MATRIX

As is well known, vulnerability is defined by the susceptibility of the population, structure and socioeconomic activities to suffer damage due to the action of a hazard.

The "Pinnacle" property of the Lúcumo gully is currently being developed into a parcel of land that in the future will hold a group of urban lots. For this reason, vulnerability is considered at a medium level. This consideration is based on what is indicated in the CENEPRED "Manual for the Evaluation of Risks Originated by Natural Phenomena" (2015).

5.1 Geotechnical Risk Matrix

Once the stratification of the geotechnical hazard matrix with the vulnerability matrix is known, the geotechnical risk matrix is estimated from a double entry matrix and the risk is rated as: very high risk, high risk, medium risk and low risk.

Table N° 14: Double entry matrix

Hazard Matrix	0.416	0.056
	0.262	0.035
	0.161	0.022
	0.099	0.013
	0.062	0.008
		0.134
		Vulnerability value

Table N° 15: Risk matrix

Very High Risk	**0.035 ≤ R < 0.056**
High Risk	**0.022 ≤ R < 0.035**
Medium Risk	**0.013 ≤ R < 0.022**
Low Risk	**0.008 ≤ R < 0.013**

6 GEOTECHNICAL RISK ASSESSMENT

6.1 Hazard Assessment

The danger was evaluated for one of the most critical section of the unstable zone (Picture N° 05), which will be concreted at the time of conformation of the slope cuts.

The evaluation of the geotechnical hazard indicates that the most critical section considered, presents a high hazard, this is expressed as the occurrence of superficial slides of rock mass or colluvial deposits product of the influence of an earthquake and to the geomechanical structure of the present rock, which is in a regular state. Also it can present rock block falls of 2.00 m < D blocks < 3.00 m

Table N° 16: Hazard Assessment

Descriptor	Valuation	Weights
Slope and S.F of the slope	Slope = 80% S. F $_{seismic}$ = 0.66	0.416 x 0.312
SMR and RMR valuation	44	0.161 x 0.280
Diameter of rock blocks	2.00 m	0.262 x 0.128
Seismic Acceleration	0.27 g	0.161 x 0.280
		∑ = 0.253

6.2 Vulnerability Matrix

The vulnerability assessment was based on assuming a medium vulnerability according to the values recommended by the CENEPRED "Manual for the Evaluation of Risks originated by Natural Phenomena" (2015), which indicates that the high vulnerability has a value of 0.134.

This value indicates houses that do not have regular maintenance, made of wood, and that are infrequently publicized in various media on risk management issues, will be affected.

6.3 Geotechnical Risk Matrix

Using the geotechnical hazard and vulnerability results, the level of geotechnical risk that would be presented in the most critical section (Picture N° 07) can be calculated, this risk reaches a value according to the following table:

Table N° 17: Risk Assessment

Hazard Matrix	0.253	**High Risk = 0.034**
		0.134
		Vulnerability Value

The geotechnical risk assessment indicates that the unstable section considered presents a high risk, this is interpreted as: the slope presents gradients greater than 60%, with a regular geomechanical structure, which would cause rock blocks fall 2.00 m < D blocks < 3.00 m, and would mainly affect homes and people with poor risk management knowledge, as well as homes commonly built with wood and with inadequate maintenance.

7 GEOTECHNICAL RISK REDUCTION

Due to the fact that the critical section considered presents a conformation of cuts in its geometry, this with the purpose of obtaining more developable area, it can be argued that:

In the zone there will be mass slides or rock block falls from the rocky outcrops, which are commonly located in the highest part of the slopes, as well as rock block detachments, results of cuts made.

The first risk reduction system consists of the installation of dynamic barriers, which is a system designed to stop rock blocks falls. This system works through the deformation of its components post-impact, which absorb energies produced by the impact of falling rock blocks.

Dynamic barriers were presented by several bidders, however, these systems must be tested and certified according to the ETAG-027 standard, which is the most rigorous guideline in the world, to guarantee that the product presented offers the best performance.

For the dynamic barriers, in the present high-risk situation; it' s recommended its installation in the upper part of the cuts, this with the purpose of containing mass slides or rock blocks falls from the upper part of the slope.

The second protection system is the installation of a slope fortification system which is designed for the protection, stabilization and control of instability in a superficial way, in order to avoid degradation of cut or slope surfaces.

This system consists of a protection net with equally distributed anchors, which ensures that in the event of a superficial rock block detachment, these blocks are retained, thus preventing them from falling.

Picture N° 06: Dynamic Barrier

Picture N° 07: Slope Reinforcement

8 CONCLUSIONS

Saaty's (1980) hierarchical analysis process is an exceptionally powerful tool for situations where it is not enough to consider quantitative components, but requires the inclusion of qualitative components and expert judgment.

In this study it has been possible to appreciate the importance of estimating the assessment of geotechnical risk in the expansion of urban areas, thus reducing or mitigating possible damage to human lives, urban and roads.

For the present study, four factors that can influence a hazard at the geotechnical level were identified, and these are: slope gradient, geomechanical rock assessment, rock block diameters and seismic acceleration.

Due to the fact that the construction of urban areas has not yet taken place, vulnerability was assumed in accordance with the "Manual for the Evaluation of Risks originated by Natural Phenomena" of CENEPRED (2015).

The use of dynamic barriers that comply with the ETAG-027 certification and anchorage systems that comply with the UNE-EN-1537 or NBR 5629 standards is recommended.

In order to contribute to risk reduction, it is recommended that the inhabitants are made aware of it, so that the probability of the risk being present is reduced.

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