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Probabilistic landslide hazard in a recurrent landslide in Colombia

Risque probabiliste de glissement de terrain dans un glissement de terrain récurrent en Colombie

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ABSTRACT: A Probabilistic method was previously used to perform Probabilistic Hazard Zonation in El Salvador. The slope angle was used as the susceptibility function. Rainfall and earthquakes are considered triggers of landslides. Zonation and modeling were performed because the probability model was initially designed to do the zonation of large areas like El Salvador to initially calibrate the model. El Salvador is a country with important problems caused by landslides triggered by both rainfall and earthquakes. Then it was an ideal scenario for an initial evaluation of the model. This paper used the same model to do the zonation of a smaller region that has had landslides problems for several years affecting road infrastructure. Shallow and deep landslides occur every day and this problem was analyzed with this probabilistic model. Due to the previously mentioned scale differences, 2-dimensional modeling of critical sections is presented, which consider geomechanical properties of the materials close to the surface. Both limit equilibrium and finite element modeling were performed to complement the zonation.
The probabilistic model calculates, for a specific region, the total probability of landslide hazard in a scenario where both rainfall and earthquakes can occur, but only one of these two events will effectively trigger the landslide. A database of "Central-America and Colombia Rainfall Induced Landslides in Fine-grained soils" and a database of "historical and worldwide Earthquake Induced Landslides" were considered and updated to reinforce the model. Seismic hazard reports and Intensity-Duration-Frequency curves "IDF" from the specific area were used.

RÉSUMÉ : Une méthode probabiliste était auparavant utilisée pour effectuer la zonation probabiliste des dangers au Salvador. L'angle de pente a été utilisé comme fonction de susceptibilité. Les pluies et les tremblements de terre sont considérés comme des déclencheurs de glissements de terrain. Le zonage et la modélisation ont été effectués parce que le modèle de probabilité a été initialement conçu pour effectuer le zonage de grandes zones comme El Salvador pour calibrer initialement le modèle. El Salvador est un pays qui connaît d'importants problèmes dus aux glissements de terrain provoqués à la fois par les précipitations et les tremblements de terre. Ensuite, c'était un scénario idéal pour une première évaluation du modèle. Cet article utilise maintenant le même modèle pour faire le zonage d'une région plus petite qui a eu des problèmes de glissements de terrain pendant plusieurs années affectant l'infrastructure routière. Des glissements de terrain peu profonds et profonds se produisent tous les jours et ce problème a été analysé avec ce modèle probabiliste. En raison des différences d'échelle mentionnées précédemment, une modélisation bidimensionnelle des sections critiques est présentée, qui prend en compte les propriétés géomécaniques des matériaux proches de la surface. Des modélisations à l'équilibre limite et aux éléments finis ont été réalisées pour compléter la zonation.

KEYWORDS: probability, slope angle, rainfall-induced landslides, I-D-F curves, geomechanical properties, earthquake-induced landslides, seismic hazard, database, zonation, modeling, susceptibility.

1 INTRODUCTION.

The approach to evaluating landslide hazard via strictly quantitative methods does not have as many references as semi - quantitative and qualitative methods. Then, when it's about considering rainfall and earthquakes as triggers of landslides, it's even more difficult to find valid and available references.

Several authors have developed methods that propose methodologies to evaluate landslide hazards. Mora & Vahrson (1994) for instance, developed a model in Costa Rica, to easily and in a practical form, classify landslide risk in seismically active regions, presenting a guide that allows the engineer to take fast decisions considering five factors: slope, lithology, soil moisture, rainfall and factors of seismic intensity. Rodriguez, Torres & Leon (2004) determined landslide hazard via a probabilistic method applied to destructive seismic events up to 2004 in El Salvador using earthquakes as triggering factor and rainfall and slope angle as susceptibility factors. Rodriguez & Yepes (2009) also worked in El Salvador using rainfall and earthquakes as triggering factors and slope angle as the only susceptibility factor due to the lack of geomechanical properties information covering all the area. This last research used a probabilistic model that considers rainfall and earthquakes simultaneously but defines that only one of them will trigger the landslide.

This limitation is tried to be covered by the current research. The probabilistic methodology was used to perform landslide hazard zonation and two-dimensional modeling using geomechanical properties close to the surface was made to consider scale differences. The probabilistic model was initially developed to study large areas like countries.

Throughout this paper, both zonation and modeling are carried out considering properties of the materials close to surface. This is because the intention is to analyze how earthquakes and rainfall can trigger all types of landslides in a slope.

The main intention of this paper is to encourage civil engineers to use probability in geotechnical engineering and to raise awareness about the need to work with numerical methodologies to assess of landslide hazards instead of using qualitative methods that don't actually give precise results.

As common definitions in the technical civil engineering accepted and valid literature, and as a way to affirm the content of this paper: Statistics is the tool and Probability is the alternative to consider several variables in an actual real life daily problem in civil engineering.

The factor of safety allows a civil engineer to evaluate several scenarios based on only one alternative of geomechanical and geological parameters. Probability allows the civil engineer to evaluate several scenarios based on several alternatives of geomechanical and geological parameters.

2 GENERAL SETTING

In order to work with probability calculations and with the intention to include variables that can actually affect slope stability, this work included: seismic parameters, rainfall parameters, the slope angle as a susceptibility value for landslide hazard zonation, and friction angle values close to the surface for two-dimensional analysis. Topography, seismicity, and rainfall information for the two landslides studied in the current research project, were provided by SGC "Colombian Geological Survey" and by IDEAM "Institute of Hydrology, Meteorology and Environmental studies" in Colombia. Two databases were updated:

- A worldwide historical database of earthquake-induced landslides, prepared by Rodriguez (1767 B.C. – 2002) and Yepes (2002 – 2007), was updated by Mosquera and Mosquera from 2009 to 2019.
- A historical database of rainfall-induced landslides in four countries of Central America (Guatemala, El Salvador, Nicaragua, and Honduras) and Colombia prepared by Yepes (1982 – 2007) was updated by Mosquera and Mosquera from 2009 to 2019.

A short description of the variables involved in the probability model and the calculations, the landslide hazard zonation, and the two-dimensional limit equilibrium analysis is included in this chapter, as follows:

2.1 *Susceptibility parameter*

Susceptibility, in this probability model, is a value between 0% and 100% or between 0.0 and 1.0, that represents the current and actual geographical and/or geotechnical behavior of the specific problematic area. The more technical information available, the more geotechnical the susceptibility function can be. Susceptibility function is a function that includes the susceptibility parameter that represents in the best probable way, how stable or unstable, the evaluated area is.

A susceptibility parameter can be: geomechanical, geological, topographic, among others. All parameters in terms of probability.

In the previous research, in which this current probability model was applied and analyzed as a first trial "Rodriguez, Yepes, 2013", it had a notorious limitation, the lack of engineering properties that could cover all the area of study. Parameters like the friction angle, the intercept of cohesion, or the shear modulus, are difficult to get, even in developed countries. These parameters would create an ideal scenario to evaluate landslide hazards in terms of probability.

Here, two fundamental reasons didn't allow the accomplishment of this task. Firstly, the model was initially conceived for large areas like a country. Secondly, there will be an evident problem of scale when dealing with geomechanical and this probability model (SGC, Colombian Geological Survey, 2016). This second reason has a strong background if it is recognized that the probability model is associated to the application and zonation of landslide hazard in large areas, geological areas, and its consequent geological scale. Then, geomechanical properties "strength-deformations-permeability" are an engineering description that is obviously associated to geotechnical areas and its consequent geotechnical scale. A geotechnical engineering scale is fundamentally different to a geological scale.

So, the probability methodology for landslide hazard zonation was applied to the two landslides in Pipiral, a Central small Region of Colombia, using the slope angle as the susceptibility parameter again. Here, the two landslides area (plan view), were divided in cells of "2.0 x 2.0 m^{2}". This division was done in order to calculate probability and to perform hazard zonation in each cell. The size of the cell was decided in terms of the geo-engineering information available. "2.0 x 2.0 m^{2}" cell, in terms of graphical zonation, is a square area where all the probability values are assigned. This second trial helped validate the model and have a better approach to the application of the methodology.

Then, in order to try to cover the limitation of including geomechanical properties in this research project, and to make it possible to refer in more geotechnical engineering terms, two-dimensional limit equilibrium analysis and Finite Element Analysis were modeled. The friction angle and the modulus of elasticity were calculated via correlations with SPT (standard penetration test) results. This item will be explained in the following chapter, in a more thorough form.

2.2 *Seismicity parameters*

Three parameters will be used to calculate the probability of landslide occurrence due to earthquakes: susceptibility function, the probability of occurrence of the critical earthquakes, and the probability that this critical earthquake triggers landslides in a specific "2.0 x 2.0 m^{2}" cell. In this subchapter, the information used to get these three parameters will be explained, and in the following chapter, the methodology and corresponding calculations will be explained in a more thorough way.

- Susceptibility function: the slope angle was used as the susceptibility function. A normal distribution formulation that better explains how slope angle influences the stability of a slope, was applied.
- Probability of occurrence of the critical earthquake: here, the seismic hazard evaluation report for the area that covers the two landslides was used (SGC, Colombian Geological Survey), and the probability of occurrence of the critical earthquake was calculated using the "Gutenberg-Richter" relationship. Seven seismogenic sources were identified. Seven geological faults that are close enough to the areas of study to influence them. The scale and the size of the landslides were the main factors to choose these seven geological faults. The area of the landslides, as mentioned above, were divided in "2.0 x 2.0 m^{2}", and the geological faults were divided in "2.0 meters" spaces. Figure 1 shows an explanatory scheme of how distances from each cell in the two landslides to the 2-meter divisions of the geological faults were measured

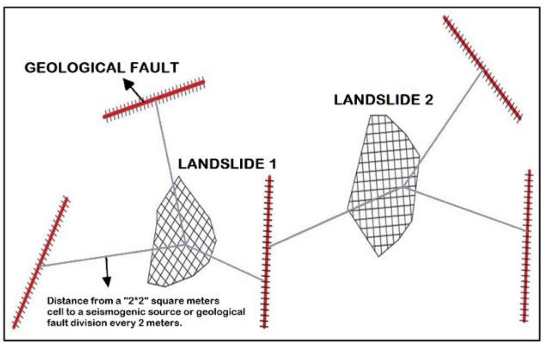

Figure 1. Explanatory Scheme of the measurement of the distance from the landslide cells and the divisions in the geological faults, to calculate the probability of occurrence of the critical earthquake (Yepes – Mosquera, 2019)

Figure 2 presents the geological faults, the location of the two landslides, the location of the specific region in Colombia and the names of the faults.

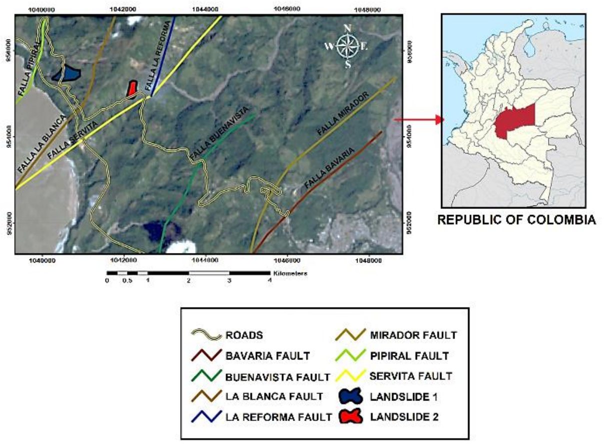

Figure 2. Geologic faults from the seismic hazard study and location of the landslides (left). Location of "El Meta" Department in the map of Colombia (top right). Names of the faults and landslides (bottom). (SGC, Colombian Geological Survey)

- Probability that the critical earthquake triggers landslides: supported and calculated by a historical worldwide database of earthquake – induced landslides (Rodriguez and Yepes, 1767B.C. – 2007) updated by Mosquera (2007-2019).

Then, as it was initially proposed by the probability model, this updated database was classified in the three failure mechanisms proposed by Keefer (1984): disrupted landslides, coherent landslides, and lateral spread and flows.

Keefer, in 1984, proposed these three mechanisms, which are widely accepted and valid in the strict geotechnical engineering terminology. They represent in a very didactical way, the most common types of landslides triggered by earthquakes.

The total earthquake-induced landslides available in this updated database are: 472 disrupted landslides, 141 coherent landslides, and 134 lateral spread and flows. Keefer presented a database of earthquake-induced landslides and a plot of Surface wave magnitude "Ms" versus Maximum epicentral distance, showing a 0% and 100% probability of slope failure due to landslides. "Rodriguez, Yepes, 2013", following the idea of Keefer, proposed curves from 0% to 100% each approximately 10%. This was plotted for the three failure mechanisms mentioned above.

The model initially intended to plot curves for each 10% of probability of failure. But, as it is actual data, and some data are close together, an approximation had to be performed.

Mosquera and Yepes (2019) updated these plots, and Figure 3 presents the landslide density curves or probability of failure for the latter mechanism: lateral spread and flows. There are two points below the 0% curve and one point above de 100% curve. They were defined as extraordinary and unusual behavior. They are out of the trend.

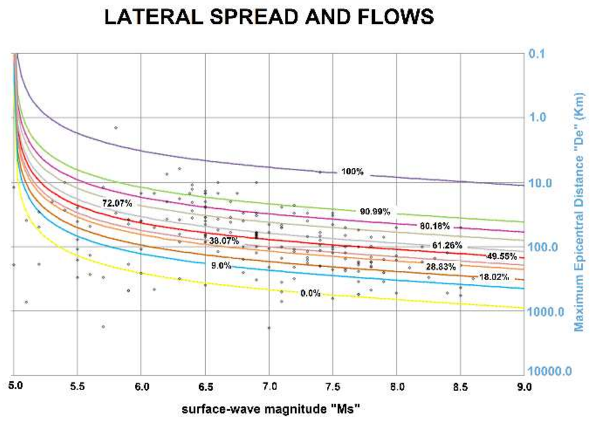

Figure 3. Landslide density curves or probability of landslide occurrence curves for Earthquake-Induced Landslides – Lateral Spread and Flows (Worldwide Earthquake-Induced Landslides, 1767 B.C. – 2019) (Rodriguez - 2002, Yepes - 2009, Mosquera - 2019)

2.3 *Rainfall parameters*

The probability of landslide occurrence due to rainfall will be thoroughly explained in the next chapter. In this subchapter, the probability model of landslide occurrence triggered by rainfall, has three parameters: a susceptibility function, the probability of occurrence of the critical rainfall, and the probability that the critical rainfall effectively generates landslides.

- Susceptibility function: the same function used for earthquake-induced landslides was used in this case.
- Probability of occurrence of the critical rainfall: here, the "Intensity-duration-frequency" curves (IDF) that were closer to the critical landslides evaluated in this project, and in a proper scale, were used. Two rainfall stations were identified: La Esmeralda and Servita. Figure 4 shows IDF curves for the "Servita" rainfall Station for return periods of: 2, 5, 10, 25, 50, 75, 100, and 500 years.

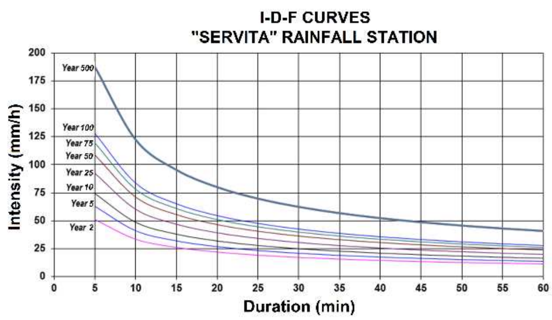

Figure 4. Intensity-Duration-Frequency curves for Servita Rainfall Station. Return periods of: 2, 5, 10, 25, 50, 75, 100, and 500 years. (IDEAM, "Institute of Hydrology, Meteorology and Environmental studies" - Colombia)

- The Probability that the critical rainfall triggers a landslide: supported and calculated by a historical database of rainfall – induced landslides in four countries of Central America where fine-grained soils are frequent in all their territory: El Salvador, Guatemala, Nicaragua, and Honduras (1982 – 2007, Yepes). This was updated by Mosquera (2007-2019), including historical rainfall-induced landslides in Colombia.

As it is possible to infer, the criteria for this database is different from the database for earthquake-induced landslides. In this case, the criteria were the type of soil, because the saturation of a slope and the generation of pore water pressure that triggers landslides works different in fine-grained soils, in coarse-grained soils, and in rocks. Landslide density curves or probability of occurrence curves were also defined for rainfall-induced landslides, in a similar form to earthquake-induced landslides, plotting the intensity of the rain that caused the landslides versus the duration of this rain. Figure 5 shows this plot.

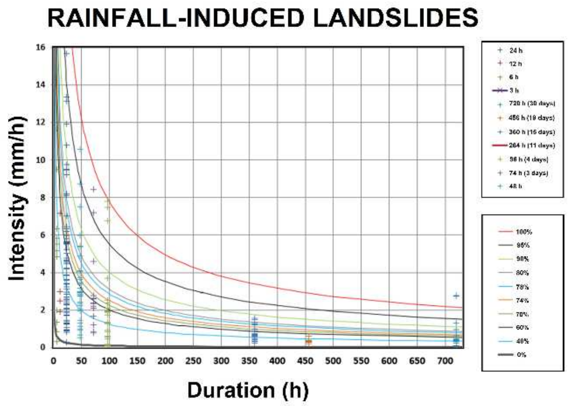

Figure 5. Landslide density curves or probability of landslide occurrence curves for Rainfall-Induced Landslides – (Rainfall-Induced Landslides in Central America and Colombia, 1982 – 2019) (Yepes - 2009, Mosquera – 2019)

2.4 *Geomechanical parameters from field investigation*

As previously mentioned, the probability model was initially proposed for large areas of study, like a country. In this scenario, the use of geomechanical properties is not actually appropriate because of the scale. That is why, in this research project, zonation and modeling are treated and analyzed separately. In this subchapter, the use of strength and strain properties will be addressed: limit equilibrium to calculate factors of safety and finite element to study deformations of the two landslides.

2.4.1 *Two-dimensional limit equilibrium and finite Element analysis:*

Using subsurface exploration performed in the two evaluated landslides and taking information close to surface in order to focus on potential ground failures, limit equilibrium and finite element analysis were performed. The results are presented in the next chapters.

Due to the difficulty to get samples like Shelby tubes to take to the lab and perform strength and deformability tests, SPT results are the only available information.

The friction angle was calculated for the identified layers from SPT results, using correlations that have been proved valid in Colombia (Gonzalez, 1999). Also, the modulus of elasticity was calculated from the same SPT results, using correlations from the accepted literature (Bowles, 2001).

The two analyzed landslides have had problems of stability for several years. Both this reason and the lack of alternatives of probabilistic and numerical methods to strictly try to find solutions to this type of problems, inspired this current project.

3. ANALYSIS METHOD

The following information was taken from "Rodriguez, Yepes, 2013" and complemented throughout this paper. Landslide hazard was defined as failure probability considering rainfall, earthquake, and slope susceptibility effects. In this subchapter, the method used to obtain that probability is briefly explained.

3.1 *Total probability*

Total probability of failure of a given slope is obtained using Equation 1. Equation one is based on Bayes's Theorem for mutually exclusive and independent events: earthquakes and rainfall.

$$\boldsymbol{P_t(F) = P(R) + P(S) - (P(R) * P(S))} \qquad (1)$$

"P_t (F)" is the total probability of failure, "P(R)" is the probability of failure due to rainfalls and "P(S)" is the probability of failure due to earthquakes.

"P(R)" is obtained using Equation 2, where "p^r" is the probability of occurrence of a given critical rainfall, "p^{fr}" is the probability that the critical rainfall induces landslide in the slope, and "S" is a function that defines the slope susceptibility to Landsliding.

$$\boldsymbol{P(R) = p^r * p^{fr} * S} \qquad (2)$$

"P(S)" is obtained using Equation 3, where "p^s" is the probability of exceedance of a given earthquake magnitude, "p^{fs}" is the probability that the seismic events induce the slope failure, and "S" the slope susceptibility. In this paper "S" was considered the same for rainfall and earthquake-induced landslides.

$$\boldsymbol{P(S) = p^s * p^{fs} * S} \qquad (3)$$

Equations (1), (2), and (3), are scalar, and non-vector product, or all the probability values, for each specific cell. The symbol "$*$" unequivocally means scalar product.

Bayes's Theorem is a practical, useful, and convenient tool in the application of Geotechnical Engineering for a real probability problem. This is very pedagogically explained in "Christian and Baecher, 2003".

4 RESULTS

The probability model presented above and previously applied to El Salvador "Rodriguez, Yepes, 2013" was applied to the two problematic and constant landslides also mentioned before, and located in Pipiral, a small region in Central Colombia. The following figures show the results of zonation and two-dimensional analysis.

4.1 *Landslide hazard Zonation*

The following figures show: the probability of failure due to earthquakes, the probability of failure due to rainfall, and the total probability including both events as factors that can occur simultaneously, but with the condition that only one of them will cause the landslide for a given cell (2.0 * 2.0 m^2).

- *Probability of failure due to earthquakes "P(S)"*

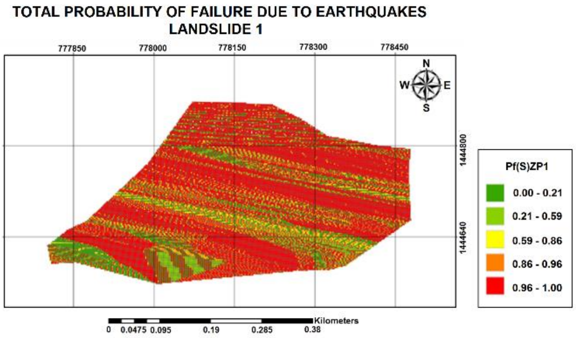

Figure 6. Probability of Failure due to earthquakes for Landslide 1 (Yepes - Mosquera, 2019)

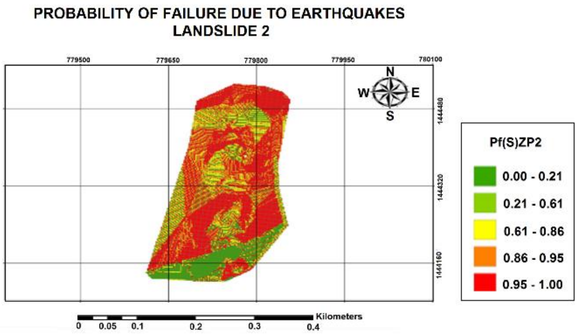

Figure 7. Probability of Failure due to earthquakes for Landslide 2 (Yepes - Mosquera, 2019).

Figures 6 and 7 represent the actual landslides occurrence of the particular region of the country. Several geological faults beside the evaluated area, and a subduction plate in the Pacific Ocean. The geological faults are included in the probability model. This zonation represents that the two (2) landslides are highly affected by earthquakes and its dynamic behavior

1.2 *Probability of failure due to rainfall "P(R)"*

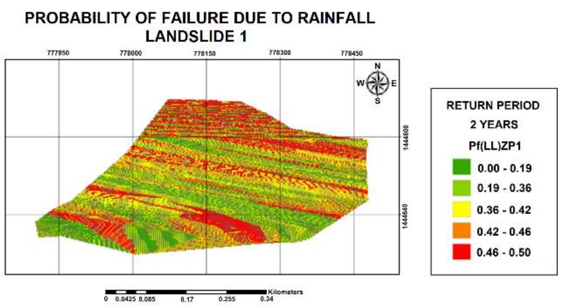

Figure 8. Probability of Failure due to Rainfall for Landslide 1 (Yepes - Mosquera, 2019).

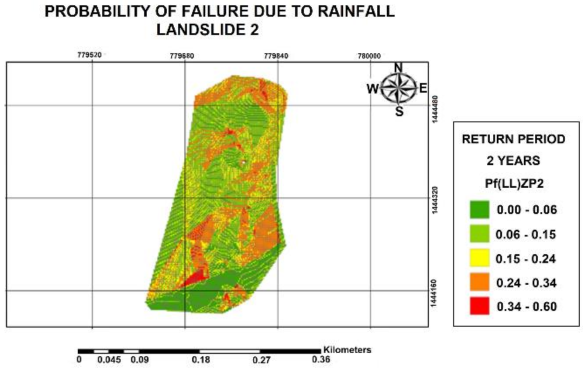

Figure 9. Probability of Failure due to Rainfall for Landslide 2 (Yepes - Mosquera, 2019)

Figures 8 and 9 also represent the actual lack of rainfall information. Periods of rainfall have been increasing with global climate change and the area of these two landslides has few rainfall stations to measure and cover all the changes in weather behavior.

1.3 *Total Probability of failure "P_t (F)"*

The following figure shows the probability of occurrence of the two events "rainfall and earthquakes", with the condition that only one of them will trigger a landslide.

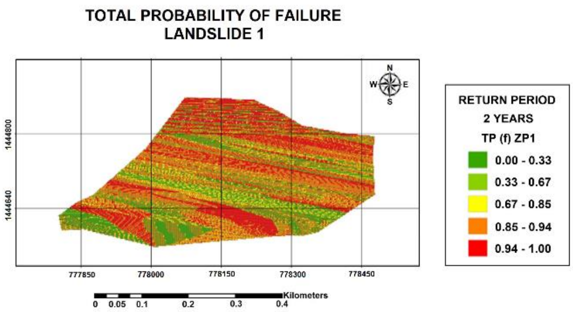

Figure 10. Total Probability of Failure for Landslide 1 (Yepes - Mosquera, 2019)

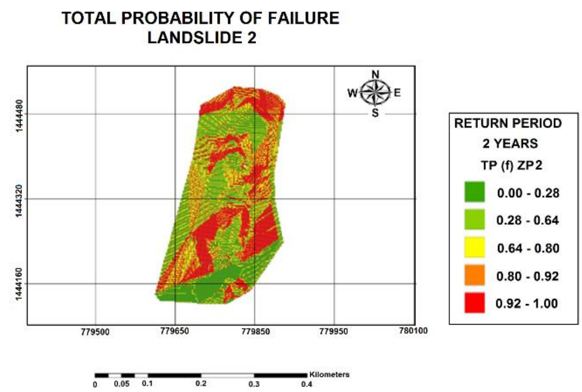

Figure 11. Total Probability of Failure for Landslide 2 (Yepes - Mosquera, 2019)

Figures 10 and 11 represent that the landslide zonation of this specific research is more influenced by the seven geological faults included in the probability model, than by the two rainfall stations considered. This is not far from reality. Colombia is a dynamic country, due to a subduction plate and an important number of geological faults, that cause very frequent earthquakes. But rainfall occurrence is fundamentally occurring with the climate change, and more stations in the evaluated areas, can help understand in a more strict way, the engineering behavior of the unstable slopes.

4.4 *Two-dimensional analysis*

Table 1 presents the geomechanical properties calculated using correlations with SPT results.

Table 1. Geomechanical properties for the layers found and defined with the subsurface exploration.

Geomechanical Properties	Strength		Deformability	
Materials	φ_u' (°)	γ_t (KN/m^3)	E (kPa)	G (kPa)
Layer 1: residual soil, fine grained	27	18	4045	1667
Layer 2: colluvial soil	29	22	16502	6374
Layer 3: sedimentary rock	32	24	19613	7551
Layer 4: igneous rock	35	24	19613	7551

Using the friction angle as the strength property for the factor of safety, and the modulus of elasticity as the deformability property for the finite element analysis, the two-dimensional analysis was carried out. Figure 12 shows, for landslide 1:

Top – left: plan view of Landslide 1. Three sections, the most critical in red color

Top – right: Factor of safety for the most critical section. The lowest factors of safety are close to surface.

Bottom – left: finite element analysis for the most critical section. Vectors showing the potential direction of the landslide. For this particular case, unstable surfaces close to surface are the most probable.

Bottom right: location of subsurface exploration.

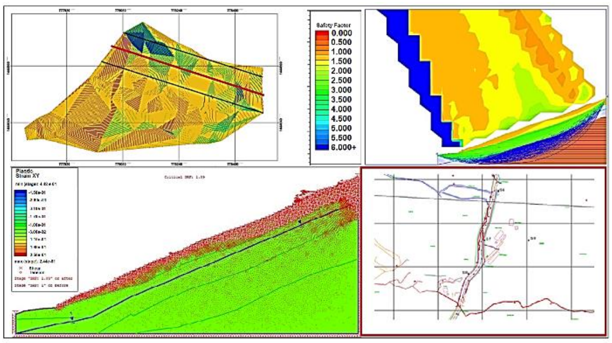

Figure 12. Two-dimensional evaluation. Limit equilibrium and Finite Element Analysis

The "sections" defined and selected in this paper are two-dimensional critical profiles that help evaluating the critical zones of the landslides.

A student version of RS2 software for Finite Element Analysis was used to analyze deformations in an elastic and elastoplastic range previous to plastic behavior. This helped prove the instability of the evaluated areas.

A student version of Slide software for Limit Equilibrium Analysis was used to analyze plastic behavior of the materials.

Limit Equilibrium is the method. Bishop simplified was the "one among several" alternatives used to simplify and do assumptions that let the Limit Equilibrium method of analysis being solved.

Elastic, elastoplastic, and plastic behavior evaluated with the mentioned software, were deterministic. These calculations were performed only to compare with the probability model.

Figure 13 shows, for landslide 2, factors of safety of 0.748 close the surface, which confirm stability problems currently happening.

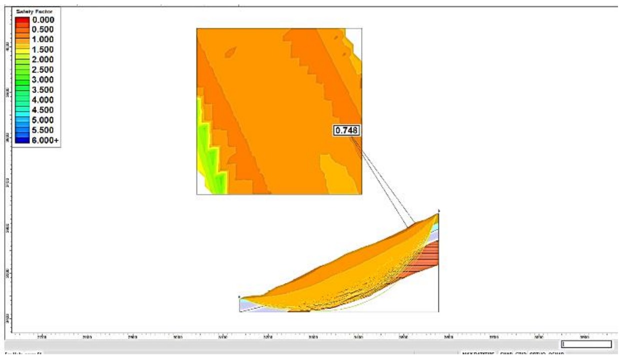

Figure 13. Two-dimensional evaluation. Factor of safety calculated via limit Equilibrium.

5 CONCLUSIONS

"Rodriguez, Yepes, 2013" was a first approach to the probability model and was applied to El Salvador. This second approach of the model showed that it actually approaches to the current reality of the landslides and the reality of the past few years. The fact that the probability of occurrence of landslide due to earthquakes includes the seismic hazard analysis of the specific area, and that the probability of occurrence of landslides due to rainfall includes information of the IDF curves close to the specific area too, gives more reliability to the results.

It's fundamental to recognize the difference between the information used for landslide hazard zonation, which is mainly "geological-seismic-hydrological-topographic", and the information used for two-dimensional analysis, which is mainly "geotechnical-pseudostatic-topographic". Even though, both ways to evaluate the stability of these critical landslides come from different theoretical backgrounds and scenarios, both show the instability that is currently occurring and has been occurring for several years in Pipiral-Colombia. The problems related to instability close to surface reflect the current reality and of recent years.

The urgent need to keep on using probability and numerical methods to evaluate hazard and eventually risk, still requires many efforts, new research ideas, and valid applications from all the professionals involved in this type of studies. The common practice of geotechnical engineering still relies too much on "qualitative, semi quantitative, empirical" methods. These methods mentioned are not the only tools. The best results come from scenarios where a combination of the formerly mentioned and quantitative-numerical-probabilistic-statistic" methods, are involved. The problem here is that the "quantitative-numerical-probabilistic-statistic" methods are the least used and probably the most accurate in many cases.

This paper has the intention to help, at least somehow, to increase the curiosity of the geotechnical engineer to realize that the use of probabilistic techniques opens an important range of scenarios that can occur, particularly taking into account the variability of the materials that nature puts on stage.

Both from the landslide hazard zonation and the two-dimensional analysis, it is possible to infer that the evident problems close to the surface may be due to erosion or loose materials in the initial meters of depth. Throughout this paper it was explained that due to the type of soil found in the landslides, it was not possible to get Shelby samples. The low cohesion of the loose soils did not allow the recovery of samples to take to the laboratory. This may be a possible cause of the instability found close to the surface.

The probability of failure due to rainfall has values up to approximately 60%. This may be influenced by the fact that IDF information comes from only two rainfall stations that are close to the two studied landslides. The probability of failure due to earthquakes has values up to 90% and more. This may be because the seismic hazard analysis has information from seven geological faults. Finally, the total probability of failure has values up to 90% and more. A conclusion here is that the problems of stability are mainly caused and influenced by the seismic behavior. Earthquakes are a common occurrence in Colombia because of the presence of many geological faults throughout its geography and a subduction zone in the Pacific Ocean.

6 ACKNOWLEDGEMENTS

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