Influence of the adopted depth of failure surface on the slope probability of failure: case study on a Brazilian slope

Marianne Bayerl Neves[1], David Bispo Ferreira[2], Eduardo Montoya Botero[3], Andrés Miguel González Acevedo[4], Vitor Pereira Faro[5], Liamara Paglia Sestrem[6], Alessander Kormann[7]

[1,2,4,5,6,7]*Federal University of Paraná*, [3]*IESB University Center*

mariannebneves@hotmail.com

Abstract

Slope stability involves many factors, e.g., topography, soil mechanical parameters, hydrological and climate site conditions and its own variability. This case study sought a preliminary implementation of an algorithm developed by the authors with the purpose of investigate the influence of the adopted depth of failure surface on the results of slope's failure probability. Landslides may occur due natural or anthropic actions and the construction of a highway is an example of anthropic action that can change stability conditions on natural slopes, as consequence of earthworks. The study site in this paper is a slope aside a highway that connects Sao Paulo and Curitiba Cities consisting on a main economical corridor between these two poles with great industrial production. The failure probability was computed with considering the variability of friction angle, cohesion intercept and matric suction by Monte Carlo Simulation on a geoprocessing software. Series of filed and laboratory tests was carried out by previous works to site characterization and its results were used to obtain input data for the current analysis. Pluviometric and piezometric instrumentation provided the necessary data to define the hydrogeological behavior of the slope. The depth of the failure surface was investigated running the algorithm for the depths of one, two, three and four meters. The results show that the probability of failure increases with the depth of the failure surface and the slope angle, which indicate that the adopted depth of the failure surface can have great influence on the results of slope stability analysis.

1 INTRODUCTION

Rainfall-induced landslides consist of a frequent geotechnical hazard that threats public safety (Ng and Shi, 1998; Zhang et al., 2014; Tao and Zhang, 2016). In tropical areas, where residual soils are abundant (Rahardjo et al., 1995), the occurrence of this type of landslides is mainly related to reduction of soil suction after rainwater infiltration in slope's unsaturated zone (Rahardjo et al. 2005; Tang et al. 2018). Moreover, slope stability verification is a theme that involves other factors, which include topography, soil mechanical parameters, hydrological conditions and the effects of anthropic actions on the natural slope state (Varnes 1978).

In this context are found the hillslopes of Serra do Mar – a system of mountains that extend more than 1500 km along the Southern and Southeastern Brazilian coast. They are regularly affected by rainfall-induced mass movements, causing large numbers of casualties and economic losses (Vieira et al., 2018; Sestrem et al., 2015; Almeida and Carneiro, 1998). The Régis Bittencourt Highway (BR 116 – PR/SP), located within the area delimited by Serra do Mar, connects São Paulo and Curitiba cities and presents frequent records of mass movements. However, the spatial distribution of these incidents indicates that there is a concentration in a specific area, called Serra Pelada, which can be represented by the slope on km 552+300 North Lane (km 552+300 NL) on the stretch (Figure 1).

Figure 1. View of km 552+300 NL at Serra Pelada region.

Source: Google Earth Pro (2019)

It is well recognized that soil parameters and hydrological conditions are not deterministic; they have uncertainties, which are associated to soil inherent variability, geologic processes and parameters definition (Phoon, 2004). That is, probabilistic analysis is necessary to assess hillslopes stability, identifying more susceptible areas regard the characteristics of adopted input data.

This paper is part of a research project about the stability assessment and monitoring of Régis Bittencourt Highway slopes. Thus, this paper sought a preliminary implementation of an algorithm developed by the authors with the purpose of investigate the influence of the adopted depth of failure surface on the results of slope's failure probability.

2 MATERIALS AND METHODS

2.1 Study Site

The study site is an area aside BR-116/SP-PR located at km 552+300 NL (Figure 1). This slope represents Serra Pelada region, which total extension corresponds to about 15 km along the highway. The criteria used to choose this slope to perform preliminary studies are the feasibility of access compared with other slopes and the record of past mass movements. Previous works (Pontes et al., 2017; Trevizolli, 2018; Batista, 2019) performed geotechnical investigation and instrumentation. Precipitation and pore pressure are monitored providing data from hydrogeological conditions of the slope.

Monitoring records of study site follow stability issues along Régis Bittencourt Highway since 2010. They show the predominance of planar slip surfaces at circa 3 m depth on Serra Pelada Region (APRB, 2019). This fact led the investigation of probabilities of failure at 1, 2, 3 and 4 m depth so that the expected, shallower and deeper failure surfaces were investigated to evaluation of the slip surface depth that shall be used in future works about Serra Pelada Region.

2.1.1 Geological and Geotechnical site characterization

Serra Pelada Region is geologic characterized by crystalline basis rock Barra do Azeite gneiss, the supracrustais sequences of the Turvo-Cajati formation and a migmatite rock intrusion (Pontes et al., 2017). The geotechnical investigation included Standard Penetration Tests (SPT) associated to rotary drilling, geophysical investigation, in situ permeability tests, determination of unit weight, moisture content, suction tests and direct shear tests (Pontes et al. 2017; Trevizolli 2018).

Direct shear tests were performed on three undisturbed samples (Trevizolli 2018). The samples, however, were not enough to capture all the variability that can occur on a slope in Serra do Mar. Thus, soil mechanical parameters – friction angle (φ) and cohesion intercept (c) – from soils with similarities to study site were obtained by literature review to establish the interval of soil parameters used in the probabilistic analysis (Table 1).

Table 1. Soil mechanical parameters

Author	Friction angle φ (°)	Cohesive intercept c (kPa)
Trevizolli (2018)	17.8 – 30.2	4.7 – 16.8
Tonus (2009)	25.0 – 36.0	6.0 – 29.0
Advincula (2016)	15.3 – 36.4	7.0 – 36.5
JCSS (2006)	21.8 – 31.0	5.0 – 10.0
Adopted	20.0 – 32.0	5.0 – 20.0

No spatial variability was adopted in this paper, since in this phase of the research only one of the slopes of Serra Pelada was treated. The area in the slope is approximately 1 hectare despite the total area of 725 hectares.

2.1.2 Hydrogeological Conditions

A rain gauge and three piezometers monitor the hydrogeological conditions on the study site. However, available pore pressure data concern July 2017 until April 2019, with reading failures over time. Another data limitation is that it does not favor the understanding of hydrogeological conditions induced by rainwater infiltration at shallow depths due to the deep piezometers installation (Figure 2a).

To deal with this limitation, data from Morro do Boi (BR-101 km 140+700) – a slope located on a highway stretch also at Brazilian Serra do Mar – was used to complement the pore pressure data from 1 to 4 m depth, once its geological and geotechnical conditions are close to km 552+300 NL slope. Four tensiometers (TENS-03, TENS-04, TENS-05 and TENS-06), and three piezometers (PZE-01, PZE-02 and PZE-03) installed on different depths (i.e. 0.50, 1.00, 2.00, 3.00, 3.90, 6.40 and 8.65 meters) were available to complement pore pressure profile (ψ) (Figure 2b) that is one of the inputs in a Safety Factor (SF) formulation, having influence on the effective stresses and therefore on the soil resistance. Figure 2 shows similarities in hydrogeological behavior from 4 m up to 16 m in both slopes: in the interval from 4 until 10 m depth the average readings remain close to zero and for depths greater than 10 m the behavior is hydrostatic.

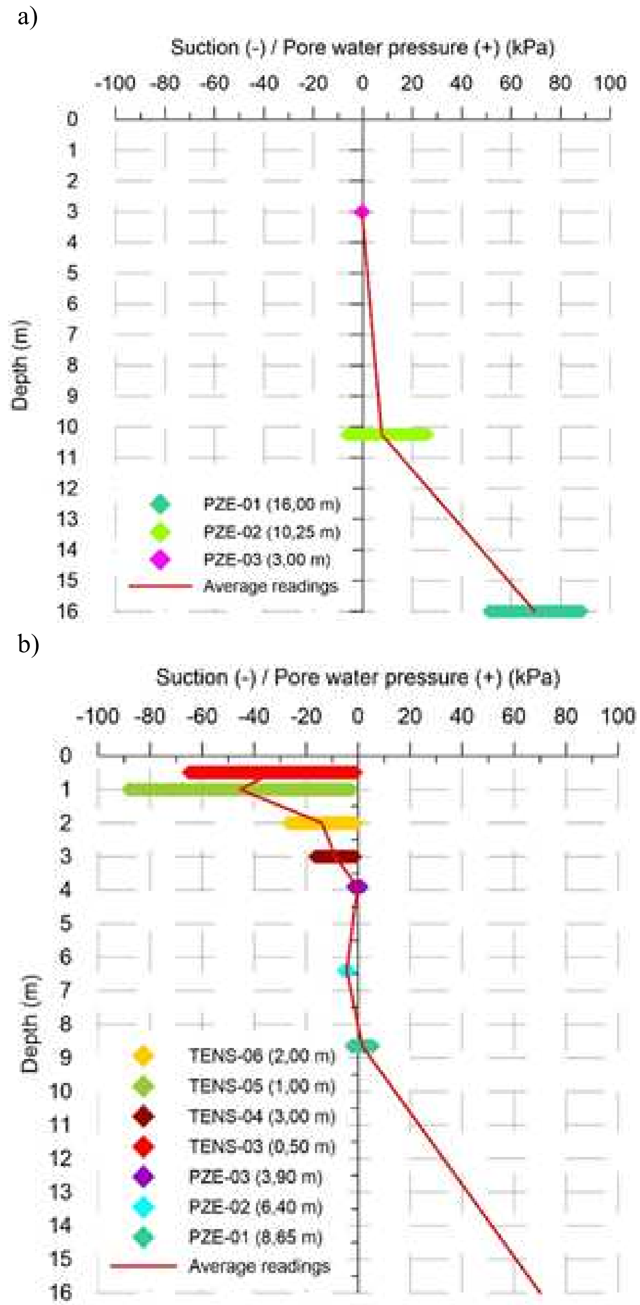

Figure 2. Positive and negative pore pressure profile from (a) km 552+300 NL slope and (b) Morro do Boi slope

The maximum and minimum pore pressure data used to calculate the failure probabilities were collected from 1-, 2-, 3- and 4-meters depth from Morro do Boi slope, allowing the definition of suction values on the unsaturated soil zone, removing outliers with a 95% confidence interval. Table 2 summarize the matric suction values used on the analysis.

Table 2. Soil suction intervals

Depth (m)	Maximum (kPa)	Minimum (kPa)
1	88.53	2.32
2	27.31	0.51
3	16.72	0.99
4	2.29	0

To verify if the matric suction values from Morro do Boi could approximately represent study site conditions, hydromechanical simulations were ran. Using geological-geotechnical characterization, meteorological data from the rain gauge installed in situ and maximum and minimum suction values from Table 2, it was possible to simulate different rainfalls occurred in the region with different initial conditions and to observe the changes in soil suction induced by rainwater infiltration. The changes in suction profiles observed in numeric simulations and by Morro do Boi instrumentation were close in 75% of the verified rainfalls, showing that slope responses to rainfall events are approximately similar in both areas. Therefore, the suction range used on probabilistic simulations were defined as described in Table 2 based on Morro do Boi slope readings.

2.2 SF Formulation and MCS

Monitoring records from highway operation show that 92% of the registered mass movements in Régis Bittencourt Highway are characterized by planar and shallow slip surfaces (APRB, 2019). Thereat, to verify slope stability, the infinite slope formulation was used in the analysis that is based on Limit Equilibrium. The infinite slope formulation used, after the inclusion of the suction effect in the soil resistance and simplifications, is found in Equation 1 that is an adaptation of the formulation presented by Fiori and Carmignani (2009).

$$SF = \frac{c' + \psi \tan \varphi^b}{\gamma_{nat} z \cos i \sin i} + \frac{\tan \varphi}{\tan i} \qquad (1)$$

Where c' is the cohesive intercept, ψ is the matric suction, φ^b was adopted as the half of φ, the friction angle, γ_{nat} is unit weight, constant and equal to 17 kN/m³, and i the slope angle.

In hands of slope map with 1 m² pixels, it was possible to run the Monte Carlo Simulation (MCS) with Safety Factors (SF) calculation for each pixel into the map.

The probabilistic analysis was carried out considering that soil suction, friction angle and cohesive intercept can vary within intervals, using an algorithm that was developed using a Python 2.7 core and a geoprocessing software. The algorithm runs a pre-defined number of randomly generated scenarios, employing the formulation in Equation 1. Due computational limitations, the number of iterations run to obtain the presented results was 500 for each pixel on the map.

Safety Factors are calculated by each algorithm iteration. Then, the SF are reclassified either as failure (SF<1) or non-failure (SF>1) and the probability of failure (p_f) at each pixel on the map is calculated by the ratio of the number of failure results divided by the number of simulations.

In the same way, the computation of the failure surface depth was made using MCS. In this time, the SF formulation was adopted being equal to 1 and the value to be calculated was the depth (z). At this time, a spreadsheet was used to the calculation of z for several slope angles, varying suction, friction angle and cohesive intercept, in the same way as occurred for Safety Factors. Each iteration provided a value of depth, making possible to obtain an average value for each considered slope angle.

3 RESULTS AND DISCUSSION

The obtained maps of p_f are depicted on Figure 3. We can observe that the deeper the failure surface is located, the higher p_f is. Indeed, as the failure surface depth increases, the acting stress is increased, while the amount of resistance due to soil suction decreases, leading to lower safety factors, approaching to SF=1, and higher p_f.

In Figure 3, is possible to see that the critical areas remain in the same regions, but its extension increases until 3 meters depth. From there, the area extent with the highest p_f does not increase as much as the probability in each pixel itself. It can indicate that failure will occur at circa 3 meters depth, which is confirmed by the records of past mass movements.

At Serra do Mar region shallow landslides are frequently registered. From analysis with safety factor formulations (Figure 4), the slip surface in the study site tends to stay at circa 3 m deep in higher slope angles, which is in accordance with field observations. The calculated depths of failure surface depicted in Figure 4 concerns slope angles higher than the lower limit adopted for friction angle, once the failure criterion used in safety factor formulation is the Mohr-Coulomb, which indicates that no failure occurs for slope angles lower than the friction angle.

Probability of failure (p_f) is a quantitative information about the safety of a slope (Neves and Botero, 2017). The adopted probability of failure classes in Figure 3 were defined based on the proposal of Dell'avanzi and Sayão (1998) apud Tonus (2009), which indicate that probability of failure higher than 0.1 compromises the safety conditions of slopes, while probabilities lower than 0.001 indicate higher performance levels.

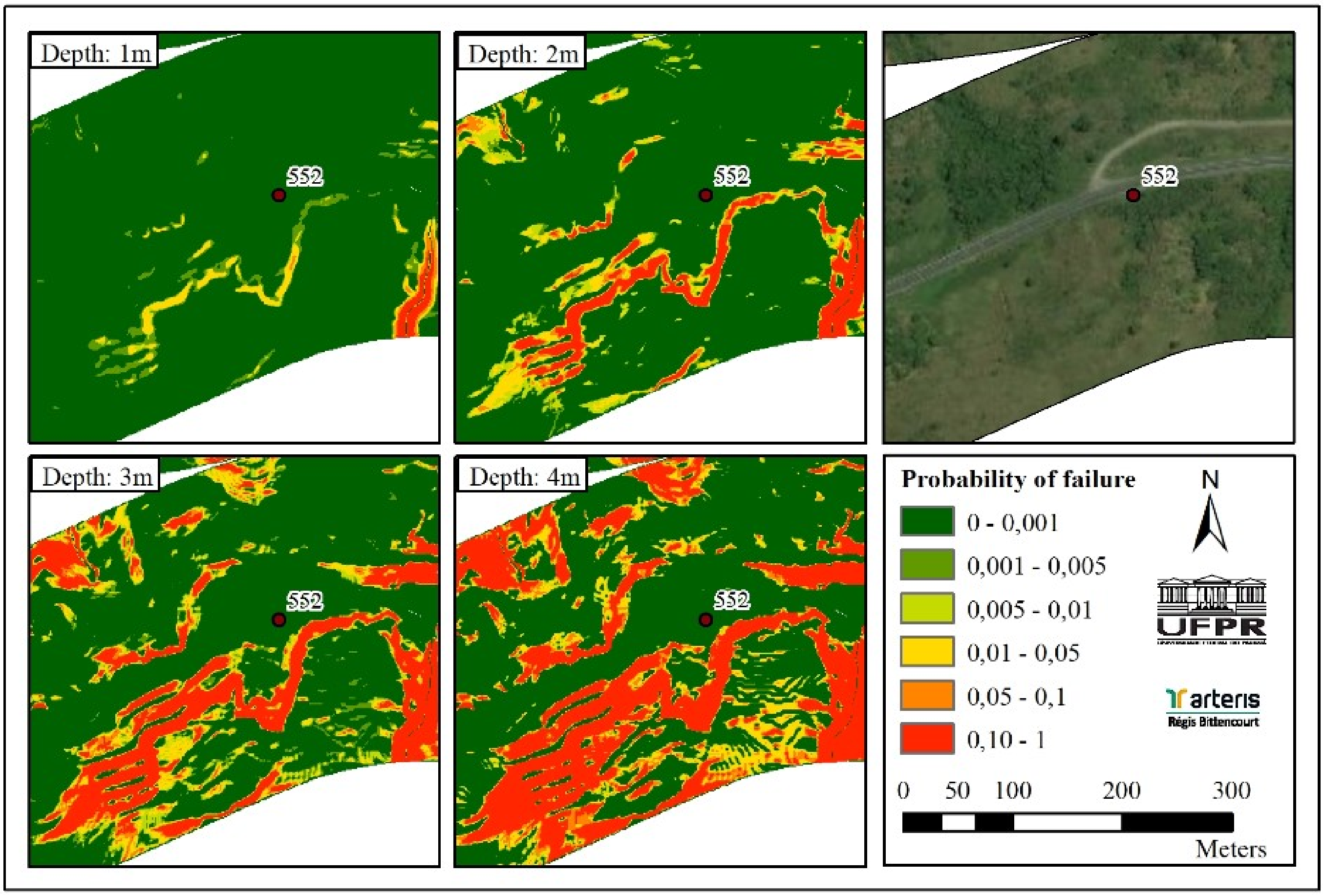

Figure 3. Calculated probability of failure at various depths

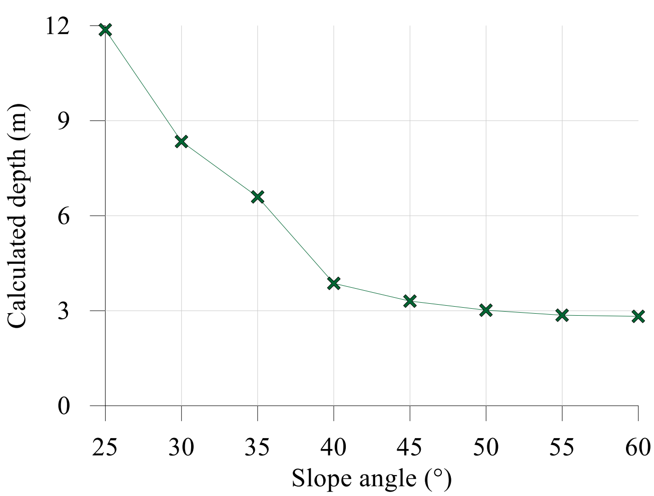

Figure 4. Variation of the calculated depth of failure surface with the slope angle.

As we can see in Figure 3, erroneously choosing the failure surface depth could greatly influence the results of stability assessment with probabilistic analysis: if the chosen failure surface in the present case study were at 1 m deep, we would obtain an unrealistic safe scenario with low p_f; while choosing a deeper failure surface, i.e. 4 m, we would obtain an unrealistic unsafe scenario with high p_f.

The spatial distribution of p_f contributes to decision-making in the highway operation safety, especially if the failure surface was correctly chosen, since critical areas with higher p_f can be identified. From Figure 3, it can be observed that the transition from safe slopes to critical areas, with more than 0.10 probability of failure, is smoother for the shallower depths. This can be related to the influence of the slope angle on the used SF formulation: steeper slopes present shallower failure surfaces (Figure 4), which implies in large probabilities of failure in these areas.

The use of suction profiles from another study site was the adopted solution to deal with monitoring limitation explained on Paragraph 2.1.2. However, this approach demonstrated being efficient to the obtainment of input parameter for the unsaturated slope stability model, once the calculated depth of failure surface reaches the field observations. An alternative to deal with the incomplete data readings could be to extrapolate the hydrostatic pore water profile from study site monitoring. This alternative would disregard the existing net flow through the soil surface, which corresponds to a boundary condition on the soil behavior (Ridley 2015).

Similar results about the influence of failure surface depth can be found at Botero et al. (2015), where infinite slope formulation was also used to determine the probability of failure on a mountainous region. Even the probabilistic analysis did not use MCS, the obtained probability of failure was higher in deeper failure surfaces and steeper slopes, while lower probability of failure was in shallower failure surfaces and lower slope angles.

4 CONCLUSION

The results on this paper showed that the probability of failure on a slope is proportional to the depth of the slip surface considered to calculate the SF. This can be in part correlated to the greater contribution of soil suction at shallower depths and reinforces the importance of adopting the correct failure surface depth in safety assessments, reproducing field conditions as best as possible. If a slip surface that is shallower than the real one is adopted, the probability of failure is underestimated, so that the safety of users on the highway is threatened. On the other hand, if a deeper rupture surface is used, the probability of rupture is overestimated, causing a sense of insecurity that does not represent reality.

It is known that the main time-variable parameter on the SF formulation is the soil suction and it have a straight relationship to the precipitation. Thus, the investigation of the suction profiles presented after rainfall events by means of instrumentation data analysis could be performed, so that input parameters can be obtained to compute monitoring maps based on probability of failure of the slopes.

ACKNOWLEDGMENTS

This paper was carried out with the support of the Technological Development Resources – RDT, of Autopista Régis Bittencourt – Grupo Arteris, under the regulation of the Brazilian National Land Transport Agency – ANTT. The authors wish to express their gratitude to CAPES – Coordenação de Aperfeiçoamento de Pessoal de Nível Superior.

5 REFERENCES

Almeida, F. F. M, and Carneiro, C. D. R. (1998) "*Origin and Evolution of the Serra do Mar*". Revista Brasileira de Geociências, 28, 135-150. In Portuguese.

BATISTA, E. F. (2019) "*Metodologias de mensuração econômica e avaliação da vulnerabilidade com aplicação em trechos da rodovia Régis Bittencourt, São Paulo-SP*". Dissertation (Master). Post-Graduate Program in Civil Construction Engineering, Federal University of Paraná, Curitiba, Brazil.

Botero, E. M. et al. (2015). "*Aplicação de Métodos Probabilísticos na Previsão Espacial de Escorregamentos Deflagrados por Chuvas – Estudo de caso: Pajarito, Medellín, Colômbia*". From Fundamentals to Applications in Geotechnics, IOS Press. In Portuguese.

Fiori, A. P. and Carmignani, L. (2009). "*Fundamentals of soil and rock mechanics: applications in slope stability*". Federal University of Paraná, Curitiba, Brazil.

Ng, C. W. W. and Shi, Q. (1998). "Influence of rainfall intensity and duration on slope stability in unsaturated soils". Quarterly Journal of Engineering Geology, 31, 105-113.

Neves, M. B.; Botero, E. M. (2017). "*Uso do Método First Order Second Moment (FOSM) na determinação da estabilidade de muros de arrimo*". In: O Simpósio da Prática de Engenharia Geotécnica na Região Centro-Oeste (Geocentro), 2017, Goiânia.

Phoon, K. K. (2004) "*Towards Reliability-based Design for Geotechnical Engineering*". Special Lecture for Korean Geotechnical Society.

Pontes, A.F.R., Trevizolli, M. N. B., Passini, L. B., Sestrem, L. P., Marinho, F. A. M., Kormann, A. C. M. (2017). "*Integration of laboratory and field investigation on the slope aside of the highway in a Brazilian coastal hillside*". PanAm Unsaturated Soils, GSP 302, Dallas, Texas, U.S.

Rahardjo, H., Lee, T. T., Leong. E. C., Rezaur, R. B. (2005). "*Response of a residual soil slope to rainfall*". Canadian Geotechnical Journal, 42, 340-351.

Rahardjo, H., Lim, T. T., Chang, M. F., Fredlund, D. G. (1995). "*Shear-strength characteristics of a residual soil*". Canadian Geotechnical Journal, 32, 60-77.

Ridley, AM (2015). "*Soil suction — what it is and how to successfully measure it*" in PM Dight (ed.), Proceedings of the Ninth Symposium on Field Measurements in Geomechanics, Australian Centre for Geomechanics, Perth, pp. 27-46.

Sestrem, L.P. et al. (2015) "*Precipitation Influence on the Distribution of Pore Pressure and Suction on a Coastal Hillside*". Soil and Rocks. v. 38,p.81-92.

Tang, G., Huang, J., Sheng, D., Sloan, S. W. (2018). "*Stability analysis of unsaturated soil slopes under randon rainfall patterns*". Engineering Geology, 245, 322-332.

Tao, B. and Zhang, D. (2016). "*Probabilistic Stability Analysis of Unsaturated Soil Slopes under Rainfall*". Geo-China, GSP 257.

Tonus, B. P. A. (2009). "*Stability and Slopes: evaluation of the limit equilibrium methods applied to a coluvionar and residual slope of Serra do Mar Paranaense*". Dissertation (Master). Graduate Program in Civil Construction, Federal University of Paraná, Curitiba, Brazil. In Portuguese.

Trevizolli, M. N. B. (2018). "*Proposal of a model for risk assessment of landslides based on scenarios of rainfall events: application on a slope of Serra do Mar* *in the PR / SP stretch"*. Dissertation (Master). Post-Graduate Program in Civil Construction Engineering, Federal University of Paraná, Curitiba, Brazil.

Varnes, D.J. (1978). "*Slope movement types and processes"*. Landslides: Analysis and Control. Special report 176 (Eds: Schuster, R. L. & Krizek, R. J.). Transportation and Road Research Board, National Academy of Science, Washington D. C, U.S.

Vieira, B. C., Fernandes, N. F., Filho, O. A., Martins, T. D., Montgomery, D. R. (2018). "*Assessing shallow landslide hazards using the TRIGRS and SHALSTAB models"*, Serra do Mar, Brazil. *Environmental Earth Sciences*, 77, 260.

Vieira, R. (2004) "*Um olhar sobre a paisagem e o lugar como expressão do comportamento frente ao risco de deslizamento*". Tesis – Departamento de Geociências, Universidade Federal de Santa Catarina, Florianópolis. *In Portuguese.*

Zhang, J., Huang, H. W., Zhang, L. M., Zhu, H. H., Shi, B. (2014). "*Probabilistic prediction of rainfall-induced slope failure using a mechanics-based model"*. Engineering Geology, 168, 129-140.