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Pluviometric Thresholds Application to Predict Slope Failures Along BR-376 Highway, in the State of Paraná - Brazil

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Abstract. In the last years, Brazil has been affected by natural hazards such as flooding and slope failures. Most of the registered slope failures are related to intense pluviometric events. Though different factors must be considered in promoting slope instability, as geological, structural and hydrogeological conditions, topography, among others, pluviometric thresholds are defined, for specific areas, in order to understand the relation between rainfalls and slope failures. The pluviometric thresholds are determined by empirical models based on real antecedent rainfall data and real slope failure occurrences in an area, with the objective to delineate zones where specific volumes of rainfall lead to slope instability. Studies of this kind can be very useful to the creation of alarm systems and mitigation plans. This study aimed to elaborate pluviometric thresholds with different scenarios for the BR-376 Highway, between km 644 to km 680 in the state of Paraná, Brazil. The pluviometric thresholds, defined for the study area, were based on the distribution of six rain gauges and its historical data from 2014 to 2018, alongside real slope failures in the BR-376 Highway. There was obtained one threshold per rain gauge and two different settings according with the hydrographic basins in the area. The pluviometric thresholds are a useful tool to the geotechnical risk management of the highway and can be validated and adjusted with the enhancement of rainfall and landslides data.

Keywords. Rainfall, landslides, rain gauges, geotechnical risk management.

1. Introduction

The influence of rainfalls on triggering landslides has been well recognized by the literature [1-2]. The rainfall events can affect the soil and rock properties by different processes, as the alteration of the shear strength parameters of the materials, the increasing of the specific weight, the advance of the saturation front in the massif causing the development of pore pressures, among others. Studies have been developed to establish rainfall indexes that are capable to induce different types of slope failures by pluviometric thresholds based on physical or empirical processes e.g. [3-5].

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The pluviometric thresholds can be defined by empirical models, based on real pluviometric events and registered landslides in a certain location. They are defined empirically by a “cloud of dots” which represents different pluviometric conditions in certain duration of days [5]. The “cloud of dots” will define the limits between conditions where landslides occur and conditions where it does not. In this context, this work aimed to establish pluviometric thresholds for an area along the BR-376 Highway with the purpose to enable its application for the geotechnical risk management of the highway. The development of the thresholds was based on different rain gauges installed along the highway, which are part of a study project from the partnership between the Federal University of Paraná, the National Agency of Ground Transportation (ANTT) and the Arteris S.A. Company. The rainfalls registered by each rain gauge are considered in the thresholds, and the data of each rain gauge was applied for a certain area of the highway, considering its influence area. In addition, all the landslides registered in the area of each rain gauge were counted.

2. Study Area

The Serra do Mar mountain range presents an extension of around 2,000.0 km between the Brazilian states of Rio de Janeiro and Santa Catarina. The study area is characterized by a strongly undulated relief composed of colluvium and residual soils originated by igneous and metamorphic rocks [5]. The area is known by presenting a considerable number of natural and artificial slopes (related to the implantation of the BR-376 Highway) which are susceptible to landslides.

The climate for the study area is described as tropical humid with average temperature of 18°C during the warmest month of the year [5]. Due to its mountainous relief the Serra do Mar presents complexity in the atmospheric flow, which causes orographic rainfalls, ascending localized and forced movements, blocking to cold and warm fronts, among others. These phenomena difficult the weather prediction in the region [6].

The rain gauges are inserted in the Serra do Mar mountain range in the state of Paraná (Brazil), distributed in two different contribution areas along the BR-376, designated [7] as North Basin and South Basin, between km 644 m and km 663 m (North Basin), and km 663 m and km 680 m (South Basin) (Figure 1). The rain gauges RG5, RG1 and RG6 are inserted in the North Basin, whereas the rain gauges RG2, RG3 and RG4 are in the South Basin. The influence area of each rain gauge was defined considering the contribution area boundaries and altitudes (Table 1).

Table 1. Rain gauges' influence area.

Hydrographic Basin	Rain Gauges	km	Influence Area Limits	
North Basin	RG5	652+900	644+000	657+000
	RG1	660+570	656+000	661+000
	RG6	662+000	661+000	663+000
South Basin	RG2	667+900	663+000	669+000
	RG3	669+300	668+000	672+000
	RG4	676+800	671+000	680+000

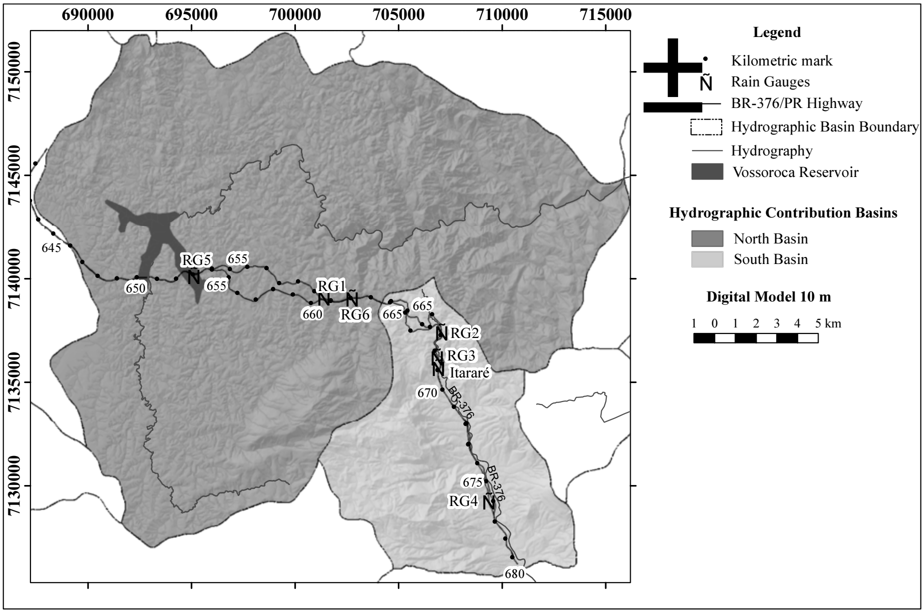

Figure 1. BR-376 Highway and rain gauges location map, modified [7].

2.1. Description of the hydrographic basins and precipitation data

Both the North and South Basins are named as São João River Basin. The North Basin has around 425 km² with elevations between 98.0 meters and 1,673.0 meters. The South Basin has approximately 104 km² and elevations of 79.0 meters to 1,556.0 meters [7]. As shown in Figure 1, the highway in the South Basin is located in altitudes of 80.0 meters to 200.0 meters and is surrounded by high elevations of up to 1,200.0 to 1,400.0 meters, whereas the highway inside the North Basin is surrounded and located mostly by elevations of around 800.0 to 1,000.0 meters. These geomorphological differences between both basins results in different pluviometric regimes, as shown in Figure 2.

Considering the average monthly accumulated precipitation, the North Basin has values ranging from 100.0 mm to 300.0 mm, whereas the South Basin presents values from 100.0 mm to around 500.0 mm. December, January and February are the rainiest months for both basins. According to the Climatic Map for the state of Paraná from the Agronomic Institute of Paraná [8], the study area presents an average annual precipitation of around 1,600.0 mm to 2,000.0 mm. The highest precipitations for the North Basin are registered mostly between the months of December and May, with values of around 75.0 mm to 100.0 mm per day. In the other months, the daily precipitation is approximately of 50.0 mm. The South Basin presents higher daily accumulated precipitation of around 100.0 mm up to 200.0 mm, approximately, also from December to May. For the rest of the year the basin presents precipitation of around 50.0 mm to 75.0 mm.

The rain gauges from each hydrographic basin present between each other a high to moderately high linear correlation [9]. For the North Basin, the correlation between rain gauge RG1 and RG5 has a coefficient of determination (R^2) of 0.818, for rain gauges RG1 and RG6 the R^2 is of 0.857 and for rain gauges RG5 and RG6 is 0.829.

In relation to the South Basin, the correlation between RG2 and RG3 has a R^2 of 0.885, for rain gauges RG2 and RG4 the R^2 is of 0.771 and for RG3 and RG4 is 0.842.

The humid climate in the area is also defined by the lower percentages of dry days for each rain gauge in different years. Since 2014, the rain gauges registered approximately less than 30% of dry days during a whole year.

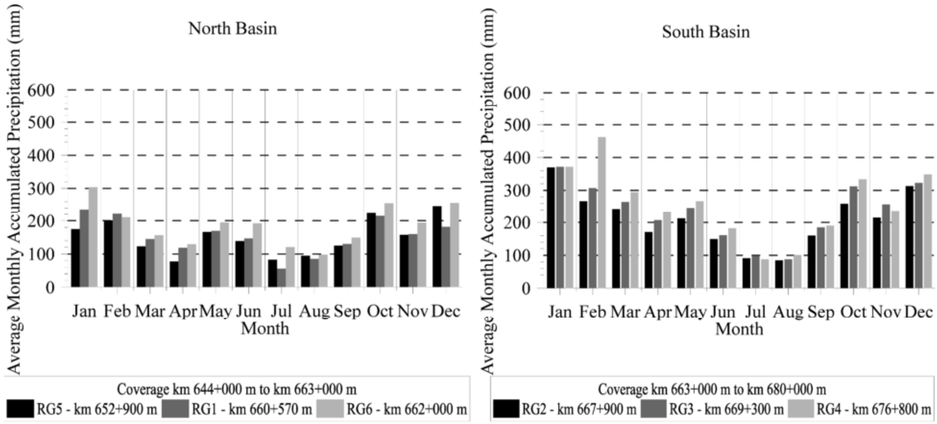

Figure 2. Average accumulated precipitation for North and South Basins.

2.2. Rain gauges correlation with Itararé Rain Gauge

The rain gauges were installed in the study area in 2014, therefore, for the landslides registered before the installation of the instruments to be considered, it was applied the precipitation data registered by another rain gauge installed in the area, the Itararé Rain Gauge (Figure 1), which is operated by Transpetro (Brazilian Oil and Gas Company).

The coefficients of correlation between each rain gauge with the Itararé Rain Gauge were calculated with the purpose to verify the proper application of the Itararé Rain Gauge data. The lowest correlation ($R^2 = 0.563$) was obtained for rain gauge RG5, which is at a higher altitude and approximately 17 km far from Itararé. The highest correlation ($R^2 = 0.765$) was obtained for rain gauge RG2. The linear correlation is classified for all the rain gauges as moderately high, which suggests the adequate application of the Itararé Rain Gauge data in this study. The highest R^2 were obtained for the rain gauges installed at the South Basin, as the Itararé Rain Gauge is also inserted in this basin (Figure 1). In general, the Itararé Rain Gauge records higher precipitations from the North Basin's rain gauges and lower precipitations compared with the South Basin's rain gauges.

3. Methodology

The pluviometric thresholds, for the influence area of each rain gauge, were developed based on previous methodology [4] and former works for the study area [5 and 10]. According to [4], there is not a single methodology that is adequate for all situations, but each region, depending on the data availability and the physical characteristics, will have a specific methodology which is more suitable. In addition, the enhancement of historical data can lead to the refinement of the methodology.

The development of the thresholds considered the daily precipitation data of each rain gauge and the date on which the landslides were registered by the concessionaire responsible for the highway. A limiting factor in the elaboration of the pluviometric thresholds is related to the fact that the date of the landslides is not always the exact date on which the event occurred, but the date when the event was registered by the concessionaire. The literature concerning pluviometric thresholds tends to fix values of daily accumulated precipitation (mm/24h) and relate it to accumulated precipitation of 24h, 48h, 72h and 96h, searching for the best configuration on which the pluviometric events that causes landslides are separated from those that do not cause these events [4].

In this study, the best configuration that fit the data was different for each basin. The North Basin's pluviometric thresholds were defined by the relation between accumulated precipitation in 24h (mm/24h or mm/1 day) and accumulated precipitation in 480h (mm/480h or mm/20 days). Whereas for the South Basin's pluviometric thresholds, the relation was defined between the accumulated precipitation in 24h (mm/24h or mm/1 day) and accumulated precipitation in 168h (mm/168h or mm/7 days). This configuration was defined considering the percentages of points in each scenario, in order that the most critical scenarios had the lowest percentages of points, which correspond to pluviometric events with no landslides registered. The landslides that were plotted in the thresholds are denominated by letters when the precipitation considered for the event was related to the Itararé rain gauge (before 2014), and by numbers when the precipitation derive from the other rain gauges (after 2014). It is important to note that the landslides occurred outside the domain area of the highway are not registered by the concessionaire and therefore are not considered in the study.

4. Results and discussions

The pluviometric thresholds can be refined with the enhancement of pluviometric data from the rain gauges and the record of landslides that occur in the study area. The pluviometric thresholds developed in this study considered previous landslides. In 2018, there was no record of landslides in the area. The year of 2018 was around 20% to 35% drier than the other years, since 2014, with the lowest annual accumulated precipitation registered in all rain gauges installed in the area, from 1,132.6 mm to 2,065.8 mm.

The thresholds for each basin are detailed in the sub-items 4.1 and 4.2. The difference between the basins, described in item 3, can be explained by their different pluviometric behavior, with higher precipitations in the South Basin, as described in subitem 2.1. As the North Basin has lower precipitations, it takes longer time (20 days) to these events promote landslides than in the South Basin (7 days). With the purpose to enable the application of the thresholds for the geotechnical risk management along the BR-376 Highway, four different scenarios were defined as alert criterias or control parameters. The lower limit separates the accumulated precipitation that do not tend to cause landslides (Scenario 1) and those that have higher probability to trigger these events. The Scenario 4 represents the occurrence of cataclysmic events, associated with daily accumulated precipitations (24h) of at least 100 mm, whereas the Scenarios 2 and 3 are characterized by conditions that can promote landslides in specific locations of the highway and are distinguished by the accumulated precipitation. The thresholds' validation and adjustment are possible with the occurrence of landslides in the area.

4.1. North Basin

The pluviometric thresholds for the influence area of each rain gauge from the North Basin correlate accumulated precipitations of 24h with accumulated precipitations in 480h (Figure 3). For the threshold from rain gauge RG1, 1.5% of the events are in the Scenario 3 and 3.5% in the Scenario 2. Although Scenario 1 has 4 registered landslides they represent only 0.26% of the points in this scenario. For the rain gauge RG5, the threshold presents 1% of the events in Scenario 2 and 0.2% in Scenario 3. The Scenario 1 has 2 registered landslides, but they represent only 0.14% of the total events. For the pluviometric threshold for the influence area of rain gauge RG6, 0.6% of the events are in Scenario 2 and 0.7% in Scenario 3. In the pluviometric thresholds from the North Basin, all the plotted points in Scenario 4 (100%) are landslides. It is also important to emphasize that the landslides plotted in the Scenario 1 (pluviometric thresholds for rain gauges RG1 and RG5) should be evaluated individually, considering other natural and geotechnical characteristics that could trigger their development aside from the occurrence of precipitation.

4.2. South Basin

The pluviometric thresholds for the influence area of each rain gauge from the South Basin correlate accumulated precipitations of 24h with accumulated precipitations in 168h (Figure 3). In the pluviometric threshold for rain gauge RG2, 0.9% of the events are in the Scenario 2 and 0.3% in Scenario 3. Thought there are 2 landslides registered in the area that are in Scenario 1, these events represent only 0.14% of the total events in this scenario. For rain gauge RG3, 2.4% of the events are in Scenario 2 and 0.2% in Scenario 3. The Scenario 1 presents 1 landslide that represents 0.06% of the events in the scenario and the Scenario 2 has 4 landslides, which represents 9.3% of the total events in the scenario. Finally, the pluviometric threshold for the rain gauge RG4 has 1.5% of the events in Scenario 2 and 0.7% in Scenario 3. The Scenario 1 has 3 registered landslides that represent 0.18% of the events in this scenario. As for the North Basin's pluviometric thresholds, 100% of the events plotted in Scenario 4 are landslides. Besides, the landslides that were registered by the concessionaire and are inserted in the Scenario 1 should be evaluated considering other factors that could trigger the occurrence of these events.

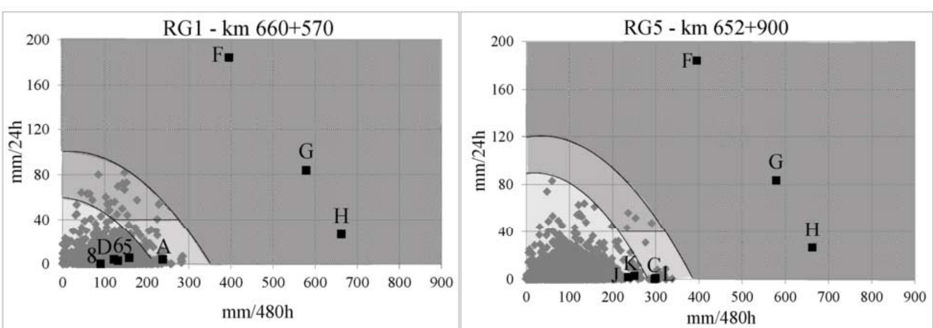

Figure 3. North and South Basin pluviometric thresholds, influence area of rain gauges RG1, RG5, RG6 and RG2, RG3, RG4, respectively.

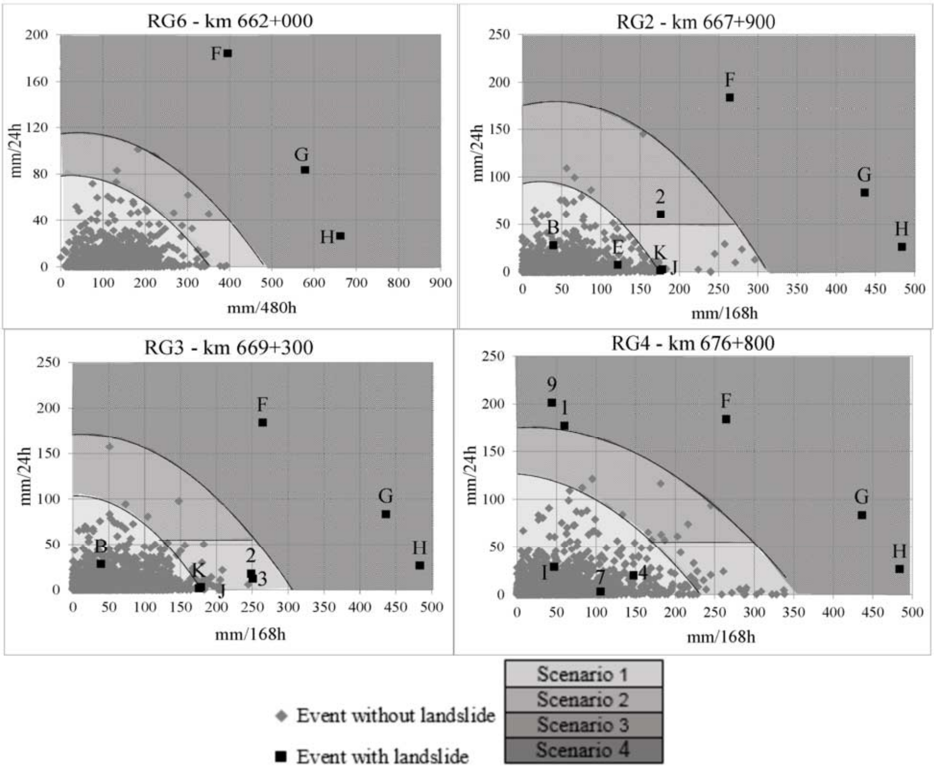

Figure 3. (*continued*) North and South Basin pluviometric thresholds, influence area of rain gauges RG1, RG5, RG6 and RG2, RG3, RG4, respectively.

5. Conclusions

The pluviometric thresholds defined in this work present two different settings, one for the North Basin's rain gauges and another to the South Basin's rain gauges. These differences are related to the pluviometric conditions of each basin. It was defined four different scenarios that could be applied in the geotechnical risk management of the highway. The Scenario 4 represents the worst scenario, where all the pluviometric conditions caused landslides in the area. Scenarios 2 and 3 represent conditions where landslides can occur and, Scenario 1, conditions that do not cause landslides in the region. Although Scenario 1 should not be related to the occurrence of slope failures, for the thresholds from rain gauges RG1, RG2, RG3, RG4 and RG5 there were landslides registered in this condition. These landslides should be evaluated individually, considering all other characteristics that triggered these events besides the occurrence of rainfall. The application of precipitation data from different rain gauges enabled the development of different pluviometric thresholds for each portion of the BR-376 Highway, considering the influence area of each instrument. This approach is important when evaluating the conditions to trigger landslides in areas with variable pluviometric conditions, as the Serra do Mar region. Each pluviometric threshold elaborated in this study can be applied for its corresponding portion of the highway to predict slope failures triggered by rainfalls.

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