Rainfall-triggered landslides: a case study in a slope of Serra do Mar, Brazil

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Abstract

All over the world, rainfall-induced landslides are one of the most frequent geotechnical hazards that threatens the public safety. In Régis Bittencourt Highway (BR-116/SP-PR), an important corridor that connects two economic poles in Brazil (São Paulo and Curitiba Cities), it is not different: there are some slopes with stability issues, mainly in the rainy season, as is the case of the studied site. Previous stability assessments were realized and showed that the study site is stable, but they concerned the analysis of pre-defined slope sections, instead of verifying the spatial distribution of safety factors throughout the study area. Thus, this paper aims to obtain the spatial distribution of safety factors, using geoprocessing tools, and considering developed pore pressures in rainfall events with higher rainfall accumulates. Rainwater infiltration in slope increases the soil water content, modifying the effective stresses until the soil resistance is not capable to keep the slope stable and triggering a landslide. By the landslide deflagration, the soil can be either saturated or unsaturated. The present study case evaluates the cases, in which the soil on the slip surface was saturated by the wetting front. Soil resistance was implemented on safety factor formulations using Mohr Coulomb failure criterion as well Lade failure criterion. Resistance parameters were obtained from shear tests performed in three undisturbed samples collected on the study site and the depth of slip surface was obtained from hydromechanical simulations, using field instrumentation data as initial conditions, once study site instrumentation alone cannot be used due its recent installation. The simulated rainfalls were defined using quantile of data series from the rain gauge installed on the study site with the complementation from two other rain gauges near there to reach 10 years of daily data series. The use of both Mohr-Coulomb and Lade failure criteria was made as comparative study inasmuch the development of rainfall-triggered landslides occurs in shallow slip surfaces leading to low normal effective stresses, which may overestimate the effect of cohesive intercept on shear strength on Mohr-Coulomb failure criterion. Lade failure criterion consists of a power function that starts on the origin of the graph $\sigma-\tau$, i.e., ignoring the existence of cohesive intercept on soils, leading to lower safety factors. The evaluated case presents a condition of low probability of occurrence, since to the simulated rainfalls capable to generate a wetting front that saturates the soil are represented by the quantile of 95% of rainfall series data, which indicates that 95% of registered rainfalls has lower accumulated values. In the present study case, the obtained safety factors using the Lade failure criterion were relatively low on the region with berms. Stability conditions in more frequent rainfall events can be obtained with unsaturated soil conditions, so complementary studies should be performed, considering the contribution of soil suction and the failure mechanism developed in the region with berms.
1 INTRODUCTION

Rainfall-induced landslides consist of a frequent geotechnical hazard that threaten public safety (D’Orsi, 2011). The occurrence of this type of landslides is related to reduction of effective stress on the slip surface after rainwater infiltration (Carvalho et al., 2015).

Mass movements in slopes are recurrent in Brazil, reaching many people. Between the years of 2013 and 2017, 833 cities had suffered from the effects of destabilization of slopes. The Southeastern Brazilian region, where the study site is located, was one of the most affected areas in this period (IBGE, 2017).

The study site is a slope found at Serra do Mar – a system of mountains that extend more than 1500 km along the Southern and Southeastern Brazilian coast. In this area, rainfall-induced mass movements affect slopes regularly, causing large numbers of casualties and economic losses (Sestrem et al., 2015; Almeida and Carneiro, 1998). Thus, the presented case study investigates spatial distribution of safety factors in a slope aside the Régis Bittencourt Highway (BR-116/SP-PR) by means of geoprocessing tools.

Knowing spatial distribution of safety factors is an important point to security management on the Highway, serving to avoid reduction on its service level. Régis Bittencourt Highway has an important role in the corridor that interconnects economic poles of the Southern Brazilian Region (Curitiba City) and Southeastern Brazilian Region (São Paulo City) (Arteris, 2019), so that stability issues aside it can cause many problems.

Evaluation of rainfall induced mass movements involves understanding precipitation events, registered by rain gauges. The interpretation of rain gauges data can be done using data series quantile that starts from the principle of statistical relativization, where the records of precipitation are evaluated in relation to all historical series of data (Souza et al., 2012; Alves et al., 2000).

A quantile $Q_p$ is defined as the limit of an interval defined to a random variable $X$, such that the probability of this random variable being less than $Q_p$ is equal to $p$, as presented in Equation 1 (Alves et al., 2000).

$$Prob(X < Q_p) = p$$

According to Gouvea et al. (2018), rainfall events can be grouped as events ranging from Extremely Dry ($Q_{0.05}$) to Extremely Rainy ($Q_{0.95}$). The values of central tendency, as the median, are represented by $Q_{0.50}$. Thus, the used quantiles on this paper are described in Table 1.

<table>
<thead>
<tr>
<th>Group</th>
<th>Quantile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme dry</td>
<td>$Q_{0.05}$</td>
</tr>
<tr>
<td>Rainy</td>
<td>$Q_{0.50}$</td>
</tr>
<tr>
<td>Extreme rainy</td>
<td>$Q_{0.95}$</td>
</tr>
</tbody>
</table>

Source: Adapted from Gouvea et al. (2018)

To analyze historical series of precipitation, it was considered as rainfall events, those whose pluviometric records exceed the value of 2 mm/day, since lower records have little influence on the soil moisture content (Souza et al., 2012). To correlate recorded rainfall in a given locality with the possibility of occurrence of landslides, rainfall thresholds can be used (Carvalho et al., 2015). An empirical threshold based on D’Orsi (2011) methodology was suggested to the study site by APRB (2019) considering rainfall accumulated values of 24 h and 72 h, since the accumulated rainfalls in these periods showed to be able to indicate tendency of occurrence of mass movements.

2 SITE CHARACTERIZATION

The study site is a slope located within the geologic formation denominated Alto Turvo Granite (Figure 1). Geological and geotechnical characterization from study site can be seen in Pontes et al. (2017) and Trevizolli (2018). Three undisturbed samples were obtained to realize shear tests and the results are presented in Table 2. All samples presented ductile behavior by shear tests.

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Natural and saturated unit weights as well void ratio and natural moisture content were obtained for the collected samples (Table 3).

<table>
<thead>
<tr>
<th>Relation</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>w (%)</td>
<td>26.6</td>
<td>34.6</td>
<td>13.8</td>
<td>25.0</td>
</tr>
<tr>
<td>e</td>
<td>0.91</td>
<td>1.19</td>
<td>0.72</td>
<td>0.98</td>
</tr>
<tr>
<td>$\gamma_{un}$ (kN/m$^3$)</td>
<td>17.2</td>
<td>15.7</td>
<td>17.3</td>
<td>16.7</td>
</tr>
<tr>
<td>$\gamma_{sat}$ (kN/m$^3$)</td>
<td>18.3</td>
<td>17.3</td>
<td>19.3</td>
<td>18.3</td>
</tr>
</tbody>
</table>
The studied slope has an extension of circa 300 m aside the highway, intercepting the mark km 552 on the North Lane. Figure 2 represents study site’s slope map and we verify slopes greater than 40°. This local characteristic corroborated to induce mass movements in the past, as can be seen in APRB (2019). To improve stability the construction of 5 berms was carried out (Pontes et al., 2017), a monitoring system was designed in 2016 (Pontes et al., 2016) and implemented in 2017 (Trevizolli, 2018). The monitoring system is composed by precipitation and pore pressure instrumentation, in order to provide hydrogeological data to investigate rainfall induced mass movements.

3 METHODS

The security level was evaluated through the infinite slope formulation implemented with geoprocessing tools. This formulation considers force equilibrium on the slip surface, calculating a safety factor with soil shear resistance and the mobilized gravitational forces (Fiori and Carmignani, 2009).

The slip surface depth was assumed as rainwater infiltration depth in soil and to obtain this value, hydromechanical simulations were carried out with initial conditions coming from instrumentation data. The simulations also provided pore pressure values to compute effective stress under the simulated conditions. Soil shear resistance in safety factor formulation was computed using both Mohr-Coulomb and Lade concepts for comparative purposes.

3.1 Local rainfall characteristics

A rain gauge was installed in the study site and transmits precipitation data since April 2017. To extend the daily precipitation series, reaching 10 years precipitation records, data from two more rain gauges were used. The complementary rain gauges are in the same basin of the study site. The use of data from complementary rain gauges was possible thanks to correlation analysis, providing the identification of similarities in their behavior. The used methodology to correlation analysis was Pearson's linear correlation and it showed moderate to strong correlation (APRB, 2019).

Previous studies (APRB, 2019; ALS, 2019) show that the relationship between the 24 h rainfall and the previous 72 h accumulated rainfall can be used to group events with similar safety levels, that may cause rainfall induced landslides. The accumulated rainfall is computed after the proposed methodology in D’Orsi (2011) (Figure 3).

Accumulated rainfall quantiles were obtained for both 24h and 72h data series to define the input rainfall in the hydromechanical simulations.
Accumulated values lower than 2 mm were removed from data series, once these kind of rainfall exercises little influence on soil moisture content (Souza et al., 2012), therefore exercises little influence on pore pressures and on soil shear resistance. Once we have three quantiles for each series the combination between them resulted in 9 input rainfall events to the simulation.

3.2 Hydromechanical simulations

Geometry and hydromechanical parameters were obtained from previous studies (Pontes et al., 2017; Trevizolli, 2018). It is known that pore pressure values are dependent from antecedent rainfall and climate conditions. To calculate effective stress instrumentation readings could be used, if large data series were available. In study site, three piezometers and one rain gauge were installed in July 2017, so that the monitoring data series is limited.

Pore pressure data from instrumentation and samples were used to establish initial conditions to run hydromechanical simulations. Two scenarios were established to represent minimum (Scenario 1) and maximum (Scenario 2) initial conditions. The piezometers are located at the point where slope surface reaches 727 m above sea level (Section 2). From there, the depths of installation are 16,00 m (PZE-01), 10,25 m (PZE-02) and 3,00 m (PZE-03). In addition to instrumentation data, water content from samples and the water retention curve were used to provide information about suction on slope surface. Two samples were obtained in the same area of piezometers installation that provided suction values ranging from 40 to 90 kPa on the soil surface (Section 2). Two samples were obtained at slope’s top (Section 1) and the water content provided suction values ranging from 50 kPa to 110 kPa. One sample was obtained at slope’s toe and the water content provided suction values around 25 kPa (Section 3) (Trevizolli, 2018). Figure 4 shows the suction profiles in soil obtained from instrumentation and samples data on the point of installation of piezometers.

3.3 Shear resistance

The shear resistance in soils is compound of two components in Mohr-Coulomb failure criterion (Equation 2) that establish a function between normal stress on the failure plane and the soil shear resistance ($\tau$). This relationship is expressed with the parameters cohesive intercept ($c'$) and friction angle ($\phi'$) (Das, 2007).

$$\tau = c' + \sigma' \cdot \tan \phi'$$

Where $\sigma'$ represents the effective stress on the failure surface, represented by Equation 3 as the subtraction of pore pressure ($u$) from total stress ($\sigma$).

$$\sigma' = \sigma - u$$

Friction, represented by the friction angle in Mohr-Coulomb failure criterion, is the resistance mobilized by friction between particles and manifests in all type of soils. True cohesion is the resistance by zero normal stress due to electrostatic attractions, but this resistance is so low on non-cemented soils that can hardly be measured, so that for practical purposes it does not exists (Mitchel and Soga, 2005). To consider this soil behavior, the curved failure envelope proposed by Lade (2010) express no effective cohesion, starting on the stress origin, reducing soil shear resistance ($s$) at low stresses, as is verified in surficial sliding. The curved failure envelope is given by a power function (Equation 4).
\[ s = a \cdot p_a \cdot \left(\frac{\sigma'}{p_a}\right)^b \]  

(4)

In which \( a \) and \( b \) are dimensionless numbers, \( \sigma' \) is the effective stress and \( p_a \) is the atmospheric pressure. The numbers \( a \) and \( b \) are obtained from direct shear tests data, plotting the relations \( s/p_a \) and \( \sigma'/p_a \) in log-log diagram as shown in Figure 5.

Safety factor formulation, using Lade failure criterion is given by Equation 6 (Lade, 2010).

\[ SF = \frac{a \cdot p_a \cdot (\sigma'/p_a)^b}{\gamma \cdot h \cdot \sin \beta \cdot \cos \beta} \]  

(6)

Where \( c' \) is the cohesive intercept, \( \sigma' \) is the effective stress, \( \phi' \) is the friction angle, \( \gamma \) is soil unit weight, \( h \) is the depth of failure surface and \( \beta \) is the slope angle.

4 RESULTS AND DISCUSSION

4.1 Hydromechanical simulations

Rainfall analysis lead to the accumulated rainfall represented in Table 3. Figure 4 represents graphically the accumulated rainfalls and the quantile, as well the events that caused mass movements.

Table 3. Rainfall quantile

<table>
<thead>
<tr>
<th>Quantile</th>
<th>24 h accumulated rainfall (mm)</th>
<th>72 h accumulated rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{0.05} )</td>
<td>2.20</td>
<td>2.40</td>
</tr>
<tr>
<td>( Q_{0.50} )</td>
<td>8.99</td>
<td>15.97</td>
</tr>
<tr>
<td>( Q_{0.95} )</td>
<td>41.66</td>
<td>67.00</td>
</tr>
</tbody>
</table>

Figure 7. Graphical representation of rainfall events

We can observe that the registered mass movements occur in areas with low dots density in Figure 7. By observing the 72h-accumulated rainfall to the quantile, Figure 7 shows that all mass movements occur with values above \( Q_{0.50} \), that is the occurrence of mass movements is related to accumulated rainfalls above the median \( (Q_{0.50}) \).
The 24h-accumulated rainfalls in registered mass movements indicate that in three of four landslide records occurred near study site presented values above 20mm, which is the approximated soil maximum infiltration rate per day. Despite the relatively low 24h-accumulated value in the fourth landslide record, this point presents 72h-accumulated value almost 2 times greater than the $Q_{0.95}$ established value, overcoming the soil maximum infiltration in this time interval.

From the hydromechanical simulations results until 5 m depth, different infiltration depths in each Scenario and each Section were obtained, reaching an average value of 1.25 m (Figure 8). We can observe that the results of rainfalls containing 72h-accumulated value equal the $Q_{0.95}$ are capable to saturate the assumed slip surface in Section 3 in all cases and in Section 2 in case of 24h-accumulated value equal the $Q_{0.95}$ in Scenario 1.

The large accumulated rainfalls, in this case represented by the $Q_{0.95}$ quantiles, were capable to create a wetting front that can saturate the soil on the slip surface, which causes loss of soil resistance by decreasing the effective stress (Lade, 2010). In the study site, the average pore pressure in the cases of slip surface saturation is 4kPa, so that this value was assumed as pore pressure in safety factor calculation, leading to effective stresses that not exceed 17 kPa.

### 4.2 Safety factors

Safety factor formulations were implemented using ArcGIS. The Mohr-Coulomb failure criterion was considered using Equation 1 and Lade failure criterion was considered using Equation 2. Resistance parameters were obtained from direct shear tests presented in Table 1. The tested samples presented the Mohr-Coulomb resistance parameters presented in Table 4 and the Lade resistance parameters are presented in Table 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$ (kPa)</td>
<td>14.1</td>
<td>16.8</td>
<td>10.4</td>
<td>13.7</td>
</tr>
<tr>
<td>$\phi$ (°)</td>
<td>27.5</td>
<td>30.0</td>
<td>30.2</td>
<td>29.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.67</td>
<td>0.76</td>
<td>0.70</td>
<td>0.71</td>
</tr>
<tr>
<td>$b$</td>
<td>0.83</td>
<td>0.78</td>
<td>0.78</td>
<td>0.80</td>
</tr>
</tbody>
</table>

The results of safety factors are shown in Figure 9. We can observe that safety factors calculated using Lade failure criterion are significantly lower than the safety factors calculated using Mohr-Coulomb. The reason is the lower resistance at low affective stresses, as shown in Figure 6.
The studied slope has 5 berms that were constructed to slope stabilization, as mentioned in Section 2. These berms have steep slope angles, which may have contributed to the result of low safety factors on the central region. However, the mechanism of rupture in this kind of slopes cannot be assumed to be infinite slope, once the geometric relationships between slope length and slope high provide the occurrence of rotational slides. In other words, safety factors verification in study site’s central area with berms would provide better results with the verification of circular slip surface as presented by Furman et al. (2018) and Trevizolli et al. (2017).

5 CONCLUSION

The spatial distribution of safety factors showed the concentration of critical areas in the steeper slopes, with slope angle bigger than 40°, in both used safety factor formulations. However, by Lade (2010) presented failure criterion resulted on lower safety factors, once it does not consider the existence of a cohesive intercept on the failure envelope. The evaluated rainfall event to obtain porepressure values presents low probability of occurrence, since the simulated rainfalls capable to generate a wetting front that saturates the soil are represented by the quantile of 95% of rainfall series data, which indicates that 95% of registered rainfalls has lower accumulated values.

Given that the Lade criterium results in unstable zones when we consider the rainfall events with higher accumulates, it is important that the slope’s surficial drainage system operates properly, avoiding rainwater infiltration and soil saturation. In addition to that, the stability issues on the study site should be followed by means of instrumentation data analysis, especially rainfall data, and regular field inspections.

Stability conditions for more frequent rainfall events can be obtained with unsaturated soil conditions, so complementary studies should be performed, considering the contribution of the soil suction, as can be seen in Botero (2013). Complementary studies should be performed also considering the mechanics of rupture on the berms, once the results presented in this paper considered the infinite slope formulation, which does not represent the stability issues on this type of 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.

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