Chapter 61

Method for analysis of the susceptibility to mass movements applied to road works

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ABSTRACT
The execution of interventions in the road network for its expansion or improvement implies interference in several types of reliefs, including undulated and mountainous. Considering the great variety of physical and anthropic factors coexisting along the routes of interest and emphasizing the occurrence of extreme rainfall events, the need to previously evaluate the susceptibility to mass movement on the hillsides bordering the roads becomes increasingly higher. The existence of studies to identify unstable areas aims to prevent the occurrence of inconvenience to users due to traffic interruption, damage to infrastructure and even fatalities. In the present research, shallow translational and rotational landslides were analyzed for a stretch of the BR-280 highway, located in Corupá and São Bento south, in the north of Santa Catarina. For this, maps of the physical environment identification were surveyed, and laboratory tests were performed to obtain the soil resistance parameters. With the data obtained, the interpretation of translational and rotational landslides was made, through the SHALSTAB and Bishop models, respectively, which were spatially applied in a Geographic Information System (GIS). Thus, a semaphore pattern was adopted for the union of translational and rotational landslide results, which indicates, on the map, the areas of greater instability, which require more attention, leading to the application of preventive measures, such as containment and drainage works.

Keywords: Geotechnical Mapping, SHALSTAB, Bishop, Mass Movements, Mapping of Risk Areas.

1 INTRODUCTION

The expansion of the Brazilian urban area implies the implementation of highways for the connection between cities or between economic centers. Many of these highways cross major regions, ranging from undulating to mountainous, being subject to natural disasters involving mass movements.

In the midst of this context, there is a need for the application of tools to diagnose areas with greater susceptibility to landslides on slopes, which border the traffic lanes. Thus, interventions can be carried out, such as the construction of containment and drainage works, in order to increase resilience to extreme rainfall events.

Therefore, it is possible to comcant a digital map that assigns, to each unit of the image (pixel), a degree of security to landslides, generating, in the end, a semaphoric map with indication of high , medium and low susceptibility classes. Thus, with the help of Geographic Information Systems (GIS) software, simulations are analyzed on maps containing spatialized information from the physical environment.

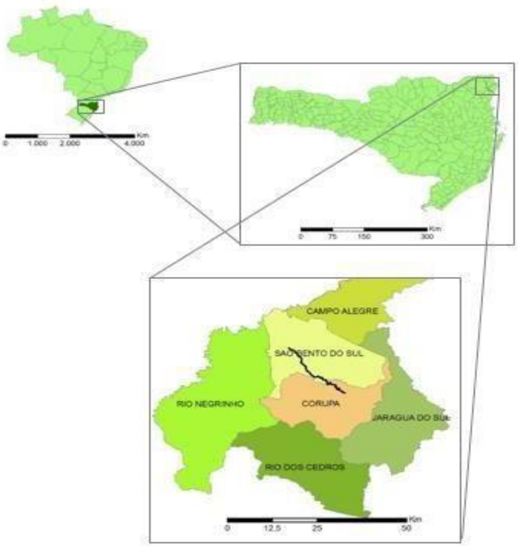
For the composition of the aforementioned analyses, topographic and geotechnical maps were surveyed, as well as laboratory tests for the characterization and determination of soil resistance.

These steps approached constitute an alternative Method of Analysis of Susceptibility to Mass Movements for application in road works, as it provides both the identification of stretches that require greater attention in the phases of design and operation of the route and the deepening of studies to propose preventive measures, which reduce the possibilities of occurrences of mass movements.

2 CHARACTERIZATION OF THE STUDY AREA

The stretch of br-280, chosen for analysis of susceptibility to mass movements, is located in the northern region of the State of Santa Catarina, passing through the municipalities of Corupá and São Bento do Sul (Figure 1). In addition, it comprises a stretch of approximately 27 kilometers, where occurrences of mass landslides have already been recorded at several points.

Figure 1. Location of the study area



(Source: LabTrans/UFSC, 2017).

To characterize the study area and to perform the stability analysis of the taludes that border the highway, a buffer of 1 km was established for each side, with the intention of defining the area of influence considered. Initially, the geotechnical and slope maps were composed, which are detailed in the following topics.

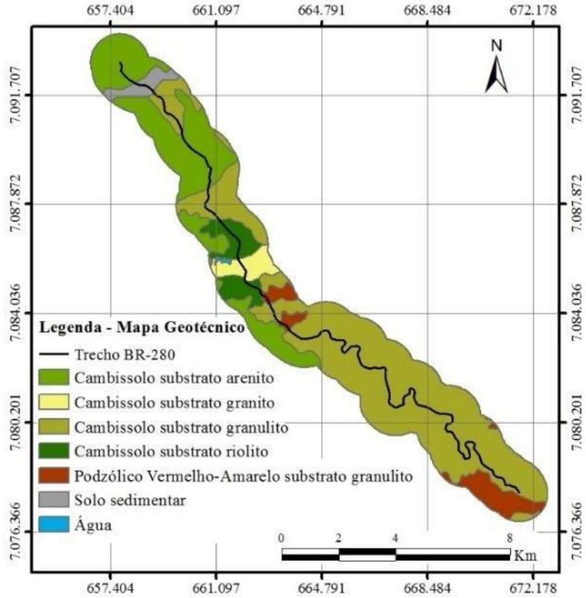
2.1 COMPOSITION OF THE GEOTECHNICAL MAP

In order to interpret more hard the physical characteristics of the soils that border the highway, the methodology proposed by Davison Dias (1995) was used. According to the author, it is possible to group soils with similar characteristics and geomechanical behaviors in polygons called Geotechnical Units. To obtain these polygons, the pedological map must be overlapbed with the lithological map, resulting in a geotechnical map. The lithological map is defined according to the predominant rock in each geological unit, observed in the description of the geological map and in field visits.

It should be noted that lithology is also used for the nomenclature of the unit, being represented by a simplified symbology in lowercase letters, preceded by uppercase letters, which indicate the pedological unit.

For the study area, according to this methodology, the resulting geotechnical map can be observed in Figure 2.

Figure 2. Geotechnical map of the study area (Source: adapted from BRASIL, 2016).



(Source: adapted from BRAZIL, 2016).

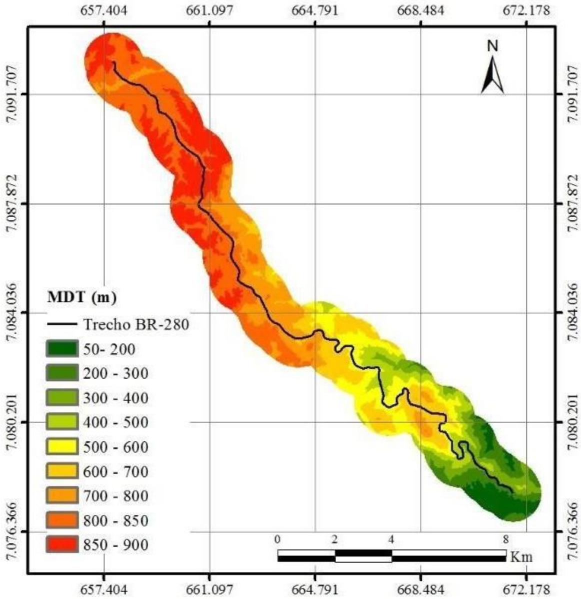
In general, the units are: Cambiolo substrate Sandstone (Ca); Cambilo granulito substrate (Cgl); and Podzolic Red-Yellow granuulite substrate (PVgl). Also noteworthy, because they contain sections of the studied highway, the units: Cambio granite substrate (Cg); and Cambide riolito substrate (Cr).

For each unit mentioned, undeformed and deformed samples were collected for laboratory tests of direct shear and soil characterization. Based on the methodology described, the results obtained in each characterization were extrapolated to the entire geotechnical unit to which it refers. Thus, a geomechanical model of the soils can be made, to be used in the simulations, together with the relief data.

2.2 RELIEF

The characterization of the relief was made through interpretations and editions of the Digital Terrain Model (MDT), shown in Figure 3.

Figure 3. Digital Terrain Model (MDT)



(Source: adapted from BRAZIL, 2016).

3 MAPPING SUSCEPTIBILITY TO MASS MOVEMENTS

The semaphoric map that identifies the areas most susceptible to mass movements was developed considering planar (shallow translational) and circular (rotational) movements in the ground. For each type of movement, an individual semaphoric map was generated, and later, the two maps overlapped, with the predominance of the most stable classes in relation to the more stable ones.

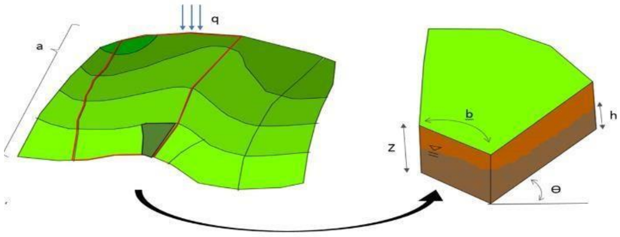
It is noteworthy that the applied method considers the location of the ruptures without estimating where the inefficient masses will be deposited. This interpretation should be made immediately thereafter and is of paramount importance , since soil volumes can reach stable areas located topographically below untittable zones. Therefore, it is relevant to analyze a significant buffer, not just a narrow strip around the highway.

3.1 SUSCEPTIBILITY TO SHALLOW TRANSLATIONAL SLIPS

The method chosen for defining zones susceptible to planar movements was the Shallow Slope Stability Model (SHALSTAB), developed by Montgomery and Dietrich (1994). This model is based on the combination of mathematical formulations for slope stability and hydrological model, attributing susceptibility to translational slips for each unit of a database, in this case a pixel of a map containing soil variables. The hydrological model used is presented by O'Loughlin (1986) and establishes a relationship between:

soil; the contribution area (a); the amount of rain (q); transmissibility (T); and slope (θ). With this, it is revealed that the saturation of the soil depends on the drainage area and the contour and length of the slope, as shown in the diagram of Figure 4.

Figure 4. Hydrological model scheme.



(Source: adapted from MONTGOMERY and DIETRICH,1994)

For the analysis of slope stability, SHALSTAB considers the system of infinite slope , and the model is based on the law of MohrCoulomb, in which the rupture of the ground occurs when the stabilizing forces do not support the forces of instability (GUIMARÃES et al., 2003). Thus, the required input parameters are cohesion, friction angle, soil depth and specific weight, together with the Digital Terrain Model (MDT), with the contribution area map and the slope map, which vary for each geotechnical unit.

With all the data inserted in the equations, the response of the model is due to the free parameter "q/T" (amount of rain/transmissivity of the soil), according to the final equation (1).

$$\frac{q}{T}=\frac{b}{a}\cdot sen\theta\cdot\left(\frac{\rho_s}{\rho_w}\cdot\left(1-\frac{\tan\theta}{\tan\phi}\right)\right)+\frac{c}{g\cdot z\cdot\cos^2\theta\cdot\tan\phi\cdot\rho_w} \quad (1)$$

For this equation, seven intervals result, which represent the stability classes, varying according to the log result(q-T).

Extreme classes represent unconditionally stable and unconditionally intractable areas. The other classes are intermediate between these two.

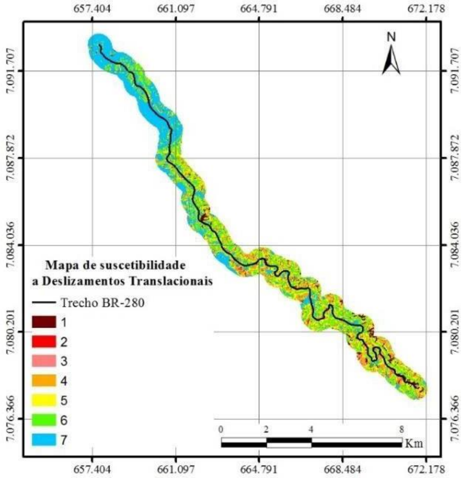
As described, this equation is applied to each pixel of the map, and classes are identified by color, ranging from red (to more unstable) to blue (to stable), as shown in Table 1.

Table 1. Classification of Susceptibility to translational slips by the SHALSTAB model.

	Classe de estabilidade	Condição
	Incondicionalmente instável (1)	$-10 < \log(q/T) \leq -9{,}9$
	< -3,1(2)	$-9{,}9 < \log(q/T) \leq -3{,}1$
	-3,1 a -2,8 (3)	$-3{,}1 < \log(q/T) \leq -2{,}8$
	-2,8 a -2,5 (4)	$-2{,}8 < \log(q/T) \leq -2{,}5$
	-2,5 a -2,2 (5)	$-2{,}5 < \log(q/T) \leq -2{,}2$
	> -2,2 (6)	$-2{,}2 < \log(q/T) \leq 9{,}9$
	Incondicionalmente estável (7)	$9{,}9 < \log(q/T) \leq 10$

The result of the SHALSTAB model for study area buffer can be observed in Figure 5.

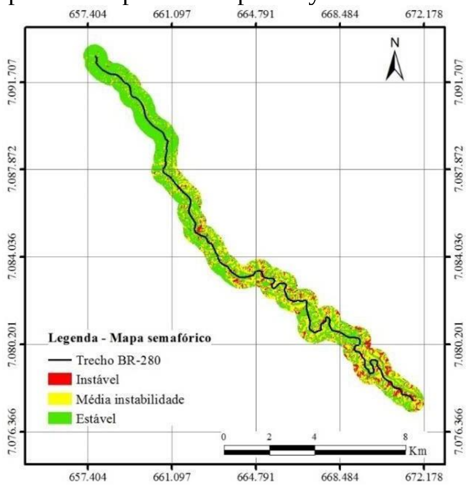
Figure 5. Smooth translational slip susceptibility map, by SHALSTAB model



(Source: adapted from BRAZIL, 2016).

In order to facilitate the interpretation of the map and to enable its union with the translational slip susceptibility map, a new classification was proposed, limiting itself to zones of High Instability (classes 1, 2 and 3), Medium Instability (classes 4 and 5) and Stable zones (classes 6 and 7). The resulting semaphoric map is shown in Figure 6.

Figure 6. Semaphoric map for susceptibility to shallow translational slips



(Source: adapted from BRAZIL, 2016).

It is noted in the map of Figure 6 that the irregular distribution of polygons, which sometimes accompany the stretches of watercourses. However, one should pay close to the spots in red, which show that the instability near the highway is evident. It is emphasized that some stretches identified as instible may have containment works already implemented, since the method applied considers the model efficient areas where anthropic interventions have not occurred.

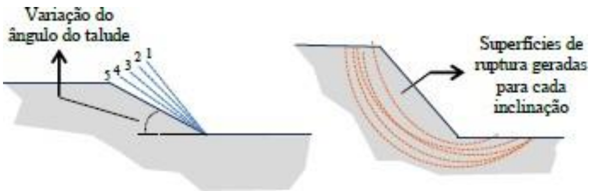
3.2 SUSCEPTIBILITY TO ROTATIONAL SLIPS

In the context of rotational mass slips, methods based on the theory of limit balance, in general, consist of analyzing the most unfavorable conditions of the forces acting in the inefficientization of the slope, compared to the resistant forces. Thus, the Safety Factor (FS) is obtained by the ratio between the resistant forces and the shear forces. In the project, the FS equal to 1.15 was adopted for a low degree of safety and, therefore, for a slope slope above which the massif would become unstable. For high degree of safety, FS equal to 1.5 was adopted. For the calculation of the FS, a slope stability software is used. In this software, it is necessary to establish, previously, the geometry of the stoneware. As input data, cohesion, friction angle and specific saturated weight are required, obtained through laboratory tests in samples collected in the geotechnical units of the studied area.

For the simulation of circular rupture surfaces, bishop's method was used, which, because it is widespread, will not be addressed in detail.

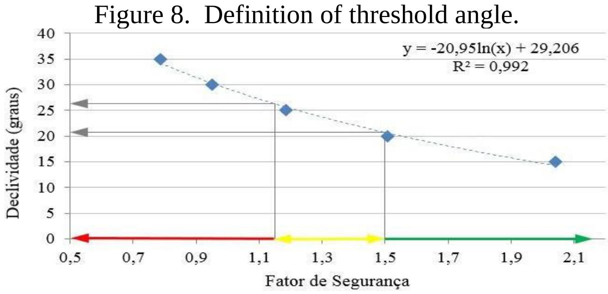
Simulations are performed for five fictitious slopes, of slopes 15, 20, 25, 30 and 35º, as illustrated in Figure 7. For each simulation, a Safety Factor (FS) results.

Figure 7. Simulation to obtain the Safety Factor (FS).



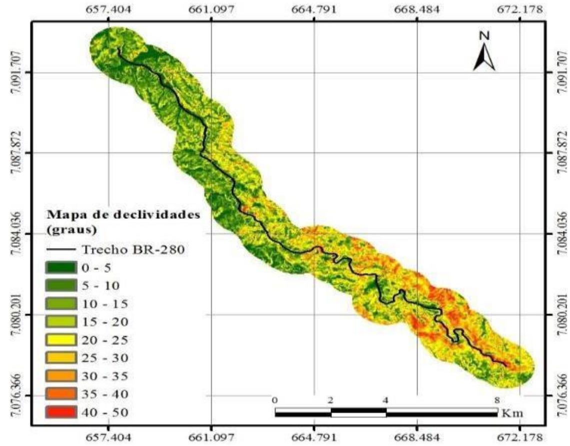
After calculating the FS values for the different stipulated slopes, a slope x FS graph is constructed. Thus, it is possible to obtain an equation of the trendline, of the logarithmic type, and the coefficient of determination (R^2). With this, it is possible to estimate what are the limit angles of a slope to configuration safe scenarios, or not, as shown in Figure 8.

Figure 8. Definition of threshold angle.



This classification can then be compared with the actual angles observed in the slope map, which is shown in Figure 9.

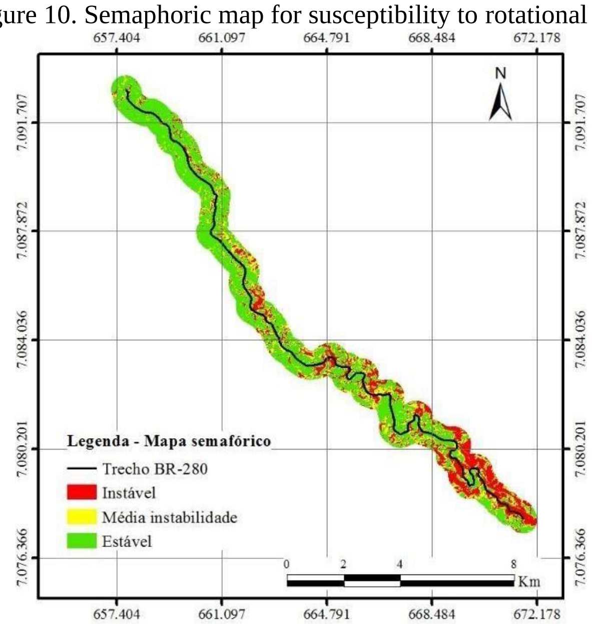
Figure 9. Map of slope



(Source: adapted from BRAZIL, 2016).

With the angles obtained for the chosen Safety Factors (FSs), a new classification can be made on this map, applied in each geotechnical unit separately. The result is a semaphoric map with division into zones of High Instability, Medium Instability and Stable Zones (Figure 10).

Figure 10. Semaphoric map for susceptibility to rotational slips



(Source: adapted from BRAZIL, 2016).

In the same way as the analyses performed for the map generated by the SHALSTAB model, zones of instability are noted in several sections of the highway. It should be emphasized that the conclusions about the two models will be addressed in the next chapter.

It is also noteworthy that the method applied in both models evaluates, as valid, the mapping of risk areas to slope slides to areas without anthropic intervention, since containment works are not considered by the model. Many of the stretches classified as instable already have walls or curtains tied, which guarantees the stability of the slopes in these places, as can be seen in Figures 11 and 12.

Figure 11. Containment structure - bolted curtain.

(Source: Google, 2017)

Figure 12. Containment structure - Retaining wall with rescan.

(Source: Google, 2017)

Thus, it is indicated the application of the method mainly for highways in the implementation phase, evaluating the natural level curves of the terrain with the changes proposed by the geometric design of cuts and landfills. With this, the stretches that require greater attention to the study of engineering techniques will be identified, in order to ensure the satisfactory functioning of the highways and the safety of users.

4 RESULTS AND CONCLUSIONS

From the results obtained with the susceptibility maps generated by the Safety Factor (FS) for rotational slips and the SHALSTAB model, a final semaric map is composed for the highway buffer,

in which: green areas are classified as Stable ; areas in yellow as Medium Susceptibility; and red areas as High Susceptibility.

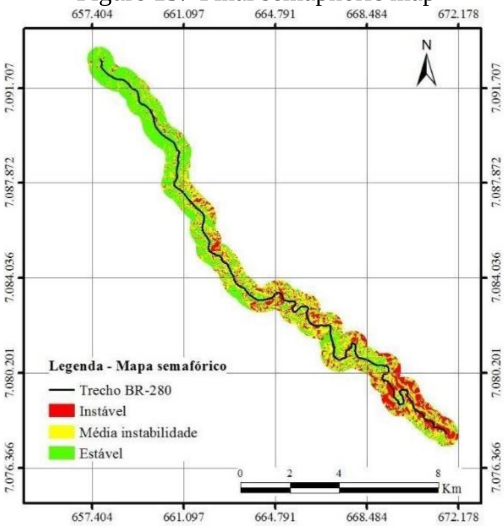
The sections with greater instability were analyzed and then compared with the places where landslides were previously recorded, in so as to verify the validity of the method.

4.1 MAPPING OF AREAS SUSCEPTIBLE TO MASS MOVEMENTS IN THE STRETCH OF BR-280

The semaphoric map for susceptibility to mass movements for the stretch of br-280 is shown in Figure 13.

With the application of the method, it was observed that the entire mapped stretch has areas with high susceptibility to translational and rotational movements.

Figure 13. Final semaphoric map



(Source: adapted from BRAZIL, 2016).

Thus, we analyze the geotechnical units that stood out because they have more areas considered marketable, in order to make a better characterization and subsequent recommendations in the geotechnical aspect. The greatest possibility of landslides in the Cgl and Ca units stands out. Residual granulet soils have high erodibility, generating changes in the geometry of the slat. In addition, there are frequent bans on the rock of origin, which become planes of weakness on the slopes.

For this reason, it is important to pay action for drainage systems, both for their design, in the design phase, and for their maintenance, throughout the life of the highway. This is mainly done in stretches where soil erodibility is high, which may cause obstruction of drainage channels. It is also emphasized the importance of conducting more frequent inspections.

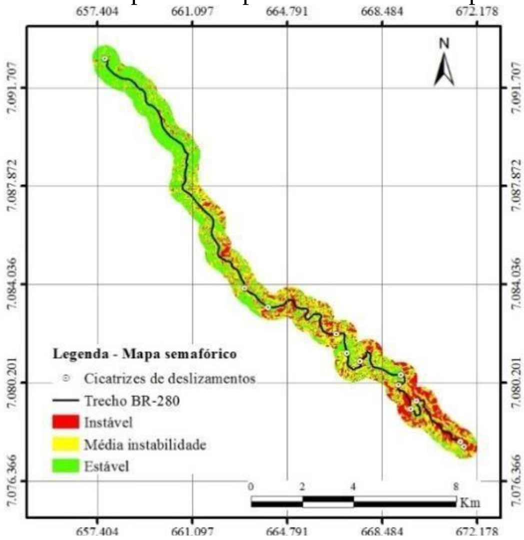
Another relevant point to be considered in the implementation and operation of highways in wavy and strongly corrugated reliefs, such as the Escarpments of serra do Mar and serras do Leste Catarinense, is the geometry of the works of rescans on soils. In addition, it is important to observe, above all, where the mapping indicates as marketable areas, because the change of slope to angles below 45º, the decrease in the height of the slopes and the increase in the width of the stools can promote the increase of the SF of these places.

As mentioned, the applied method evaluates the areas without considering containment interventions. Thus, the importance of carrying out specific investigations on each slope in areas pointed out as instable in the final semaphoric map is emphasized, in order to obtain representative data for the proposition of the best engineering solution.

4.2 VALIDATION OF THE APPLIED METHOD

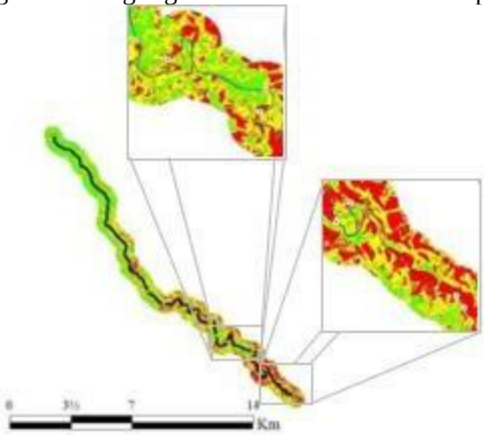
In order to assess the applicability of the method for similar road works, the overlap of geographic points was made, where mass movements have already been recorded with the semaphoric map obtained (Figure 14 and Figure 15).

Figure 14. Overlap of scar points with the semaphoric map



(Source: adapted from BRAZIL, 2016).

Figure 15. Highlight of the main instible excerpts.



(Source: LabTrans/UFSC, 2017)

Through the analysis of the map with the points of scars recorded, it was found that all landslides occurred in areas mapped as unastable.

Thus, it is expected that the method in question can serve as an aid for the management of projects on highways, so that mass movements in traffic lanes are prevented, ensuring the safety of users.

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