The influence of topographic scale in mass wasting susceptibility modeling applied to a pipeline in southeastern Brazil

1. Introduction

The purpose of mass wasting susceptibility assessment using a Geographic Information System is to assign, in a regional scale, places were these events are more probable to take place. Fernandes & Amaral (1996) consider that the main purpose of mass wasting susceptibility maps is to provide information about the probability of mass wasting occurrence, dividing the whole area in certain landscape in zones with equal susceptibility. Although these maps have not the purpose of calculate the stability of hillslopes, they should provide information on spatial and temporal probabilities and the magnitudes of the mass wasting in a landslide prone area.

The scale used to assess landslide susceptibility in steep hillslopes is very important to better describe the role played by the conditioning factors. The way which the digital elevation model (DEM) is obtained by interpolation or by mesh has an enormous influence in determining the main topographic parameters of this surface, like the contributing area, the flow direction, the slope and the hillslope curvature. These parameters are important to calculate the safety factor (SF) of these hillslopes, which may be used as inputs to deterministic models or to susceptibility indexes hazard maps. Special attention must be given to hillslopes where human occupation has already taken place, including the construction of houses, roads and pipelines.

Here we will present a variety of studies on mass wasting susceptibility modeling applied to a pipeline in steep hillslopes of Serra do Mar, close to the city of Rio de Janeiro, where mainly creeping process are occurring. In these numerical experiments we used both deterministic (e.g., SHALSTAB - *Shallow Landslide Stability Model* and TRIGRS - *Transient Rainfall Infiltration Grid-Based Regional Slope Stability Analysis*) and empirical models (e.g., SMORPH - *Slope Morphology Model*), as well as a modification of this model in order to detect areas affected by creep processes. Besides, we also tested a model based on soil and rock properties mapped in the field (*IPT Model*). In order to characterize the influence of topographic scale in our ability to predict landslide susceptibility, the simulations were carried out in scales 1:1.000, 1:10.000 and 1:50.000.

2. The study Area

The Serra do Mar is a mountain range nearby the Southeastern Brazilian coast in the states of Rio de Janeiro, São Paulo, Espírito Santo and Paraná with hilltop elevations varying from 300 to 2.000 meters. The study area is located in a steep hillslope near the coast on the state of Rio de Janeiro, just west of Rio de Janeiro city. An important pipeline goes through these W-E oriented hillslopes, which are mainly composed by Precambrian metamorphic rocks as gneisses and migmatites, locally known as Rio Negro Complex (Silva Jr., 1991).

Hillslopes in this area are continuously monitored by a variety of geotechnical instruments, as inclinometers , piezometers and pluviographs. Because it is located at the southern slope of a mountainous area, it is affected by orographic rains and maritime fronts, with higher rainfall values than nearby regions in lowlands. Most of rainfall happens from October to April, when summer storms may attain daily total values above 300mm. Because of the pipeline, many geological and geotechnical studies have been carried out in this area and the main results are included in technical reports of the ORBIG pipeline (from 2000 to 2004) as well as in thesis and dissertations in Brazilian universities. These studies have shown that creeping and landsliding processes in this area are triggered by intense rainstorms when high water tables are generated.

The applicability of the susceptibility maps generated to this area, using the models mentioned above, was validated by comparing the sites predicted as unstable with those where shallow landslides and creeping processes took place in the past.

3. Assessment of Mass Wasting Susceptibility using DEM

In landslide deterministic models that incorporate hydrological equations it is crucial that the DEM generated permits a good representation of the morphological patterns observed in the real landscape, taking into account the drainage restrictions and the water runoff pathways. Guimarães (2000) stated that the DEM generated by *Topogrid* has less residuals values than the ones obtained by other interpolators. In the current work all the DEMs where generated with *TopotoRaster* from *ArcGis*. *Toporaster* in the newer version of *Topogrid* in *ArcGis 9.0*.

The way in which the interpolation is done in order to get the center value of each cell of the DEM may have important analytical effects depending on how much adjacent are the values in order to generate a continuous surface. Some authors state that the interpolation can produce less residuals than processes generated by a triangular irregular network (TIN), suggesting that a quadratic interpolation should be adopted, due to the fact that most parameters derived from the DEM are provided by mathematical calculations where quadratic surfaces are adjusted to the surface which we want to derive (Wood, 1996).

The errors derived from the DEM can affect the flow routing calculations both in surface and sub-surface, as well as in the computation of the contributing area and other hydrological variables (Endreny e Wood, 2001). In a DEM hydrologically corrected usually all the water that enters in a cell flows to downhill cells resulting in almost no residual balance in this cell. On the other hand, a DEM without this hydrological coherence have many sinks and a residual balance.

A coherent DEM is usually smooth, with almost no place to accumulation of water and low residuals. High residuals promote abrupt changes in soil transmissivity and porosity invalidating the DEM to hydrological analysis. In this case the DEM is inconsistent and produce results with no meaning to hydrological analysis.

The calculation of the topographical variables is made through quadratic surfaces which should adjust to the DEM surface. These are used in most GIS software and are based on the work of Zevenbergen and Thorne (1987), and Horn (1981) [*apud* Burrough, 1988]. With the quadratic function adjusted to the DEM it is derived the curvature, the slope, and the aspect depending on the size of the window.

The flow direction calculation is based on the changes of slope or elevation, and it can have multiple directions or not depending on the algorithm used. The variations derived from these calculations may generate cumulative enormous differences in other parameters like the contributing area, the wetness index, and the compound topographic index.

The flow calculation has influence in the calculation of slope susceptibility where the contributing area is used. Most of GIS softwares use the algorithm that distributes the flow in eight directions (D8), but this is an unrealistic premise. In order to solve this problem many flow algorithms were proposed as the multiple direction algorithm (Quinn, 1991) and the Dinf algorithm (Tarboton, 1997). Landslide susceptibility models like SHALSTAB (Dietrich & Montgomery, 1998) and TRIGRS (Baum et al, 2002) compute flow directions in order to get the contributing area and the mass wasting susceptibility.

4. Assessment Models Used

SHALSTAB (Dietrich e Montgomery 1998) is a physically-based model that uses the Infinite Slope analysis associated with hydrological equations to define landslide susceptibility levels, varying from -10 to +10. In the scenarios simulated in this study, for simplification, soil cohesion was set to zero. The sub-surface flow is assumed to be the same as the overland flow, and it is modeled using a Darcian type equation. The model resolution is the length of the cell in the DEM previously generated. The SHALSTAB model can be present by the following equation:

$$\frac{q}{t} = \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right)\frac{b}{a} sin\ \theta \tag{1}$$

where a is the drained area for a cell, b is the length of the cell, θ is the hillslope angle, ϕ is the internal friction angle of the soil, ρ_s is the specific mass of the soil and ρ_w is the specific mass of the water. The ratio log (q/t) is calculated for each cell in the grid, defining a hydrological rate which is the susceptibility index, meaning the ratio of flow (q) with the transmissivity (t).

The topographic ratio a/(b sinθ), on the other hand, estimates how much water can accumulate in that specific cell and emphasizes the effect of flow convergence in low slope angles, characterizing processes like soil creep.

Another approach based on the model SMORPH (Shaw and Johnson, 1995) and adapted to include the contributing area was called SMORPHacc. The basic difference is that places with high contributing area and low slope angle are classified as prone to creeping process. This model uses the hillslope profile curvature, the plan curvature, the slope gradient and the contributing are to assess areas subjected to landsliding and creeping processes. The contributing are calculated by this model uses the algorithm proposed by Quinn (1991). One advantage of this model is that it only uses parameters derived from the DEM to calculate the susceptibility, without requiring field mapping. The figure 1 shows the relation among contributing area and the areas where creeping is occurring.

Two important parameters used when describing hillslope morphology are the slope gradient and the curvature. The slope gradient effect is directly correlated with landslide frequency in steep slopes and it may also contribute to deflagrate catastrophic debris flows. In wet climates, slow mass movements like creep can be triggered even in gentle slopes.

Hillslope shape (or form) influences mass wasting by its effects on soil and water distribution. Areas with convex curvatures (crest) disperse overland flow avoiding the formation of saturated conditions in the soil. On the other hand, areas with concave curvatures favors surface and subsurface water convergence, developing high water tables and contributing to the slope instability.

Another model used in this study was the IPT model (IPT, 2004) which also considers other mass wasting processes, like rock fall and soil creep by combining hillslope angle, curvature and geotechnical properties mapped in the field. This work done by IPT to assess the susceptibility in the pipeline area of Sao Sebastiao.

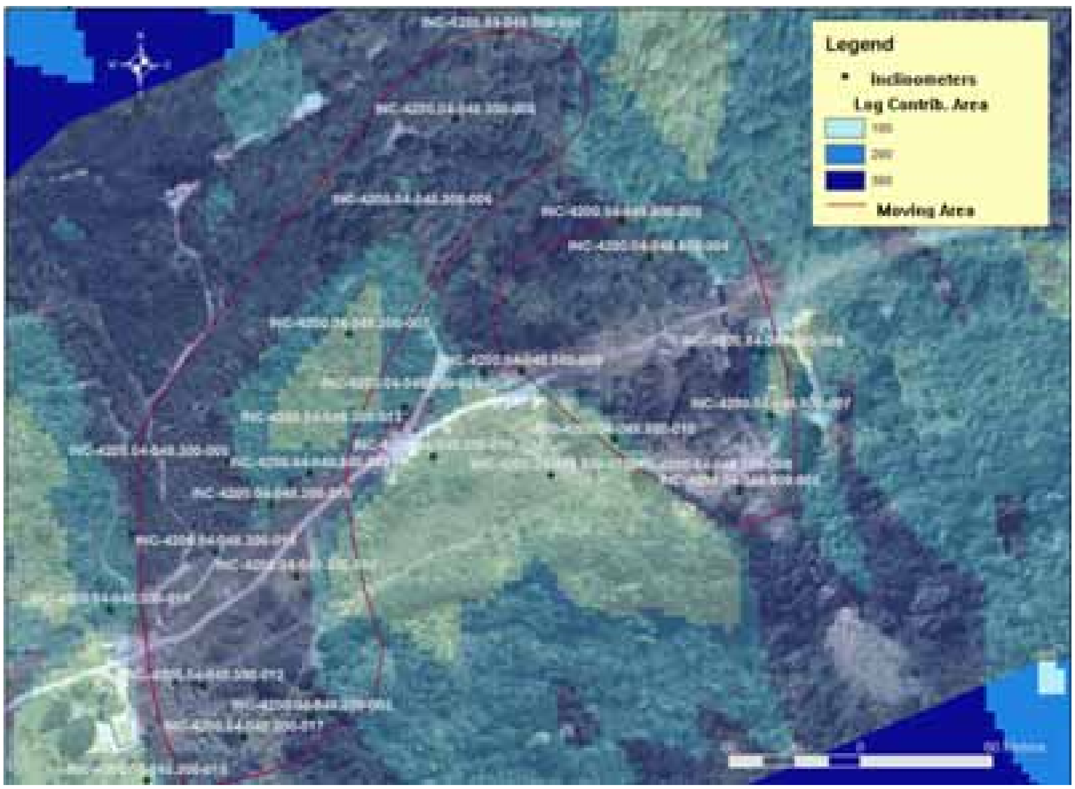

Figure 1 – The creeping area (red lines) with inclinometers assigned by their labels and showing that the process is occurring in high contributing areas.

5. Numerical Simulations

The parameters used on the simulations carried out with the SMORPHMacc model are showed on table 1. The class area attributed as composition of numbers to assign the susceptibility. This table is a composition of numbers having in the cents the contributing area, in the tenths the slope in percent, and in the unit the curvature. For example the value 251 means medium contributing area, slope greater than 70% and curvature concave. Places like this are prone to landslide. While the value 321 means high contributing area, slope angle between 7 to 14 degrees and curvature concave indicating places prone to creeping. Red colors indicate high susceptibility, yellow colors indicate medium susceptibility and green colors indicate low susceptibility.

The parameters used on the IPT model (table 2) were almost the same as the ones used on the SMORPHacc model, with the exception of the contributing area and the geotechnical mapping.

The simulations with the SHALSTAB model did not consider soil cohesion, while the angle of internal friction was set to 33 degrees and soil specific weight to 18000 N/m^3. The simulations were carried out considering the 1:50.000 and the 1:1.000 scales. The implementations were conducted on Spatial Analyst of ArcGis 9.1 and ArcMap using ArcObjects (Rabaco, 2005).

Table 1 – Parameters applied to SMORPMacc

Assessment: LL - Landslide Low CM - Creeping Medium RFH - Rock Fall high
LM - Landslide Medium CH - Creeping High
LH - Landslide High

Slope:
0 a 14% - 10
14%-24% - 20
24%-47% - 30
47%-70% - 40
>70% - 50

Curvature:
Concave – 1
Plan – 2
Convex – 3

Log of contributing area:
1/3 all element with low values– 100
1/3 elements with medium value – 200
1/3 elements with high value -300

111 LL	112 LL	113 LL	121 LL	122 LL	123 LL	131	132 LL	133 LL
141 LH	142	143 LM	151 LH	152 LH	153 LL	211 LL	212 LL	213 LL
221 CM	222 LL	223 LL	231 LH	232 LL	233 LL	241 LH	242 LM	243 LL
251 LH	252 LH	253 LM	311 LL	312 LL	313 LL	321 CH	322 LL	323 CM
331 LH	332 LL	333 LL	341 LH	342 LM	343 LM	351 LH	352 LH	353 LM

Table 2 – Parameters applied to IPT model

Assessment: LL - Landslide Low CM - Creeping Medium RFH - Rock Fall high
LM - Landslide Medium CH - Creeping High
LH - Landslide High

Slope:
0 a 20° - 10
21 -30° - 20
>30° - 30

Curvature:
Convex –1
Plan – 2
Concave – 3

Geotechnical mapping:
rock A1 to A4 – 100
residual soil – 200
coluvium - 300

111 LL	112 LL	113 LL	121 LL	122 LL	123 LL
131 RFH	132 RFH	133 RFH	211 LL	212 LL	213 LL
221 LL	222 LL	223 LM	231 LM	232 LM	233 LH
311 CM	312 CM	313 CH	321 LM	322 LM	323 LH
331 LH	332 LH	333 LH			

6. Results and Discussion

Figure 2 shows the topographic maps in scales 1:1000 and 1:1.000 of the study area.

Figure 3 presents the results obtained with the SHALSTAB model, at the scale 1:1.000. In this simulation the drainage basin water divide wasn't mapped because of lack of topographic data and the SHALSTAB model doesn't detect hillslope instability in known creeping areas of the ORBIG pipeline. The SHALSTAB model has the main purpose of detect landslides, and this area has main occurrences of creeping process. The absence topographic water divide data, in scale of 1:1.000, affected the quality of the DEM generated for the whole basin and, consequently, the calculation of the contributing area for each cell in the grid. A similar problem took place when using the SMORPHMacc model and a new intermediate scale (1:10.000) was used.

This fact did not cause any problem for the other simulations carried out here because the models did not require the computation of the contributing area for each cell.

By comparing the results obtained by these models with the sites in the field with known instability it can be attested that the best results were obtained by the IPT model which uses the geotechnical soil properties mapped in the field, the hillslope angle and the hillslope curvature. The results also showed that at the 1:50.000 all the models presented landslide susceptibility. The SHALSTAB model considered the areas of steep cliffs as sites of high landslide susceptibility because it used constant geotechnical parameters to assess the area. At the 1:10.000 scale, the SMORPHMacc model correctly assessed the area, as showed in figure 4, while the SHALSTAB model (with cohesion set to zero) did not present good results due to the fact that the area have hillslope with angles smaller than 14°.

Figure 2- Scales of assessment . The small area with 1.000 x 400 m shows the area mapped in scale 1:1.000 wheres the all area of the picture show the area mapped in scale 1:10.000.

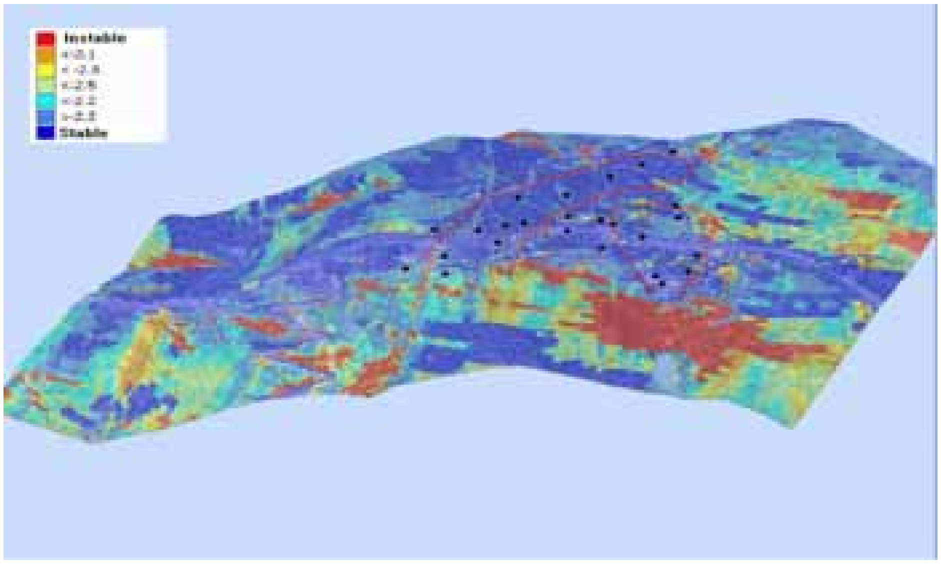

Figure3 – Landslide susceptibility obtained by the SHALSTAB model at the scale 1:1.000 where the water basin divide wasn't mapped. The area with creeping process is considered stable.

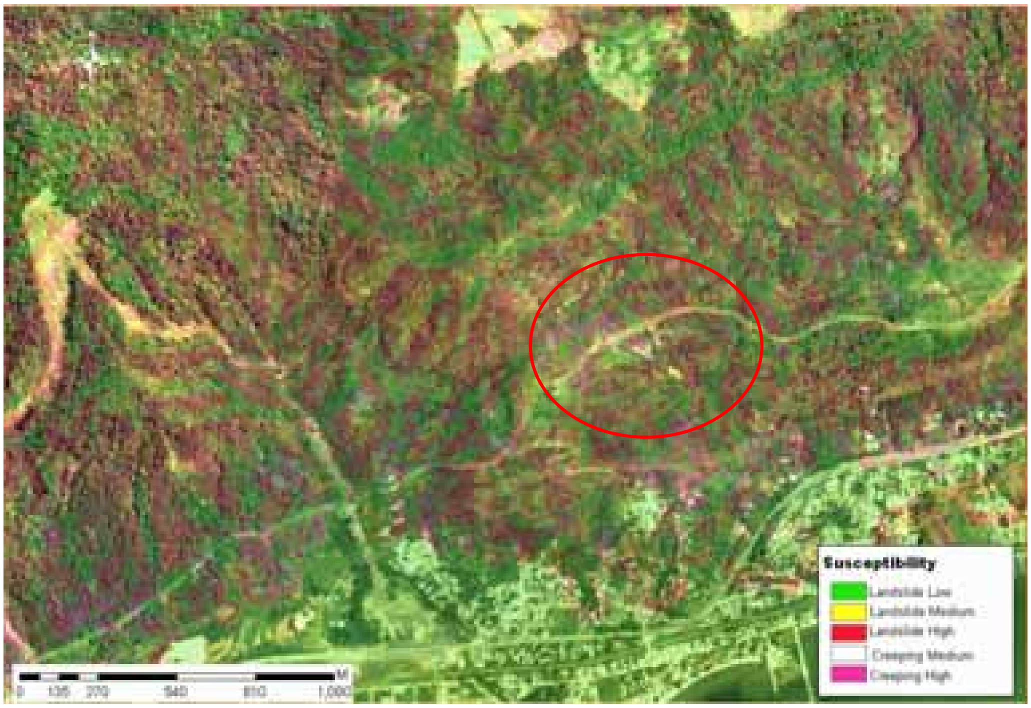

Figure4 - Assessment obtained by SMORPHACC with topographic scale 1:10.000, with a circle on the studied area.

6. Conclusion

The SMORPHacc model, which considers the effects of contributing area, although only using parameters derived from the DEM presented good results in detecting areas prone to creeping and landslide processes. The IPT model presented the best results attesting the importance of a careful analysis of soil geotechnical properties in the field. The SHALSTAB model didn't detect most of the unstable sites which might be due to the fact that the DEM was incomplete, as well as the deep soils and the low hillslope angles. Such behavior attests that the SHALSTAB model is more suitable to be used in areas with steep slopes and shallow soils. The results presented here show that for a better landslide prediction topographic data must be available for the whole drainage basin and not only for the hillslopes considered as potentially unstable. Besides, the combined usage of different landslide models may improve our ability to predict where and when hillslope failures will take place in the future.

8. References

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