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Understanding shallow landslides in Campos do Jordão Municipality – Brazil: disentangle the anthropic effects from natural causes in the disaster of 2000

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Abstract

Located in a mountain area of Southeast Brazil, the municipality of Campos do Jordao has been hit by several landslides in recent history. Among those events, the landslides of early 2000 were significant for the number of deaths (10), the population affected and the destruction of infrastructure that caused. The purpose of this study is to assess the relative contribution of natural and human factors in triggering the landslides of the 2000 event. To achieve this goal, a detailed geotechnical survey was conducted in three representative slopes of the area to obtain geotechnical parameters needed for slope stability analysis. Then, a set of numerical experiment with Geo-Slope software was designed including natural and anthropic factors separately. Results showed that natural factors, thus is, high intensity rainfall and geotechnical conditions, were not severe enough to trigger landslides in the study area and that human disturbance were entirely responsible for the landslides events of 2000. Since the anthropic effects used in the simulations are typical of Brazilian hazardous urban areas, we concluded that the implementation of public policies that constrain the occupation of landslide susceptible areas are urgently needed.

1 Introduction

Due to the combination of frequent heavy rain of high intensities on landscapes dominated by narrow valley and steep slopes, large areas of the southeast and south of Brazil are naturally susceptible to landslides. In addition, population growth, increased urbanization (about 90% of Brazilian population live in urban areas), and expansion of urban construction into hazardous areas have led to an escalating impact of this natural disaster. Consequently, landslides are directly associated with loss of lives, property and infrastructure damage, and environmental destruction. During 2011, for instance, mountains regions of Rio de Janeiro State suffered several landslides that caused more than 1,500 deaths and severe damage to the urban and rural infrastructures (Coelho Netto et al., 2013).

In spite of floods (generally gradual flooding) being the most disrupted natural disasters in terms of economic damages ad population affected, landslides have been considered the most severe in terms of dead toll (Londe et al., 2014). Although landslide and flashfloods usually affect heavily urbanized downtown areas, it is also recognize that poor population living in the outskirts are more vulnerable to these types of disaster. Increased landslide hazard, for instance, has been related to the improper cut-and-fill construction of self-built housing on steep slopes, after the removal of forest cover. In addition, because of the lack of collection systems, sewage is disposed into the hillslope soils further increasing the risks of triggering landslides, not to mention the health risks associated with the lack of sanitation.

Among those areas affected by landslides in SE Brazil, the municipality of Campos do Jordao has been hit by several events since the seventies. The most recently severe landslides occurred in the early days of 2000, leaving 103 people injured, 10 fatalities, and more than 423 houses at risk of collapse (Londe et al., 2014).

Early warning system used by the civil defense in Campos do Jordão and by CEMADEN are based on threshold values of 72 h accumulated rainfall, derived from empirical studies (Tatizana et al., 1987; Santoro et al., 2010). In 2000, rainfall was monitored every 24 h at 7:00 am using manual rain-gauges, and the threshold value for triggering landslides were based on previous studies in other areas of Brazil. Since the accumulated rainfall values responsible for the occurrence of the landslides of 2000 were well below the critical line proposed in previous studies (Tatizana et al., 1987), it was not possible to conduct the pre-emptive evacuation of many hazardous areas.

Although empirical rainfall thresholds are successfully used in operational warning systems to predict shallow landslides (Lagomarsino et al., 2013), critical rainfall thresholds for triggering landslides vary due to regional and local precipitation distribution, slope morphometry, soil characteristics, lithology, microclimate and geological history (Crosta, 1998; Van Asch et al., 1999). Therefore, the reliability of empirically derived critical rainfall threshold depends entirely on the availability of a significant number of cases relating the occurrence of landslides and rainfall conditions. In this sense, Guzzetti et al. (2007) lists as regional thresholds those covering regions with a few to many thousands square kilometers and having similar meteorological, climatic and physiographic characteristics, whereas for local conditions the geomorphology and climate regime are considered to be applicable to areas that range in the order of hundreds of square kilometers.

After the event of 2000, new critical 72 h rainfall thresholds values for landslides were proposed for the area. In addition, the Civil Defense of the State of São Paulo established new critical rainfall amounts for visually monitoring critical areas in order to detect early signals that may indicate the imminence of a landslide. However, the peak rainfall intensities recorded in the event of 2000 did not repeat even since, while irregular occupations continued in many landslide prone areas. Therefore, a detailed study of the event of 2000 is relevant not only because its extreme characteristic, but also with the perspective that memory of the 2000 event is dim and its impacts is largely underestimated among many local residents.

In this context, for a limited number of data hydrologic models are relevant for investigating precipitation induced shallow planar landslides (Terlien, 1998). Given the lack of detailed data form historical landslides events in the municipality of Campos do Jordao, the aim of this study was to understand the factors responsible for triggering the landslides of early 2000 in Campos do Jordao using a numerical model of slope stability. We analyzed several scenarios that included the relative influence of natural and anthropic factors that prevails in the area, and identified the most critical factors responsible for the severe landslides of 2000. In addition, we analyzed if the threshold rainfall values establish by the Civil Defense are adequate for early warning of landslides occurrence taking into account the today´s occupation patterns of landslide prone areas.

2 Material and Methods

2.1 Study site

The study site is the municipality of Campos do Jordao, of the State of São Paulo, located in a mountain region along the Mantiqueira Hills (Figure 1). In geological and geomorphological terms, the Jordan Fields plateau is a crystalline plateau block with elevations of more than 2,000 m above sea level and bordered by steep cliffs that rise approximately 1,500 m over the adjacent Paraiba valley (Almeida, 1976). The relief, strongly conditioned by the structures and lithologies of the area, is characterized by the presence of high hills and erosion of grandstands. On the basis of these amphitheaters occur peat depressions (Modenesi-Gauttieri and Hiruma, 2004), where deposits of organic clay of varying thickness are found. The geological and geotechnical characteristics of the deposits of organic clay and its quite sensitive behavior to sudden human interventions that alter their original equilibrium conditions have conditioned the slopes stability in the urban area of the municipality of Campos do Jordao (Ogura et al., 2004).

The area where Campos do Jordao is located was occupied by Portuguese settlers during the XVIII century. During the hygienist movement (late XIX and early XX centuries), various health facilities were established in the town, mainly for tuberculosis treatment. Since 1940, the town experienced a large population growth and urban expansion due to the development of tourism: the number of inhabitants increased from 13 thousand in 1950 to more than 50 thousand according to the estimates, with density of 164.76 pop/Km^2, 99.3% of which live in the urban area (IBGE, 2016).

The process of accelerated urbanization, specially from the 70s, of areas with unfavorable geotechnical characteristics, has been pointed out as responsible for most of the natural disasters in Campos do Jordao (Ridente et al., 2002). Table 1 shows the most important events in terms of dead toll and damages recorded in the area.

In the case of the event of 2000 (Figure 2), which is the focus of this study, rainfall began on 31/12/1999, and continues almost interrupted for 4 days with high intensity rainfall bursts. According to the Brazilian Center for Weather forecasting and Climate Study – CPTEC, daily rainfall from 31/12/1999 through 05/01/2000 was, respectively, 78.5, 101, 120, 60, 144.5 and 10.5 mm (Ridente et al., 2002). Landslides associated with this event, were considered to be one of the most severe in urban areas in Brazil, since hundred of landslides occurred, mostly in slopes in poor neighborhoods where house are constructed over cut-and-fill areas.

Based on the landslides events of 1972, 1991 and 2000, Ridente et al. (2002) proposed an approximation of the critical rainfall necessary for the deflagration of landslides in Campos do Jordão, revealing that, in most cases, landslides are due to occur after three-day rainfalls of about 200 mm, with a daily rainfall of at least 70 mm during the last day analysed. The Civil Defense Preventive Plan of the State of São Paulo uses three indexes of precipitation accumulated in three days (60, 80 and 100 mm) as critical thresholds to enter into warning level (Santoro et al., 2010). These thresholds was based on the studies carried out by Tatizana et al. (1987) and has been considered a critical value for issuing early warnings based on rainfall observation and forecasting.

Aiming to develop relationships for the prediction of mass movements in the area, Ahrendt (2005) attempted to correlate precipitation with the occurrence of landslides based on the critical intensity curves obtained by Tatizana et al. (1987) for Serra do Mar in the municipality of Cubatão, and by D'Orsi (1997) for Serra da Mantiqueira in the Municipality of Rio de Janeiro. Results showed that the occurrences of Campos do Jordão were below the critical lines of those areas, indicating that the rainfall intensities required for triggering landslides in Campos do Jordão are much lower if compared to the other sites. Therefore, the study of Ahrendt (2005) concluded that rainfall characteristics that triggers landslides in Campos do Jordão are very unique and a different and more detailed approach was needed.

Considering the limited historical data of landslide occurrences and the few previous studies in the area that makes extremely difficult to define accurate critical threshold rainfall values that triggers landslides, in particularly, the effects the accumulated rainfall on the water movement and its relationship to rapid mass movements.

The Brazilian National Centre for Monitoring and Early Warnings of Natural Disasters – CEMADEN began to monitor Campos do Jordão by the summer of 2012. Most of the occurrences were observed in cut-and-fill slopes, with evident contribution of wastewater and micro drainage deficiency. Recent history did not recorded occurrences of great magnitude; however, the destruction, or even the prohibition of occupying damaged houses, is a recurrent problem.

2.2 Soil moisture monitoring

Soil moisture was monitored in every hourly interval to a depth 3.0 meters along the 12 months (01/01/2016 to 12/31/2016), using two EnviroScan™ probes installed next of the borehole SD-03 (Figure 3). EnviroScan™ probes are installed into customized access tubes manufactured by Sentek Pty. Ltd. Inside of the EnviroScan™ probe were distributed six Sentek capacitance sensor. The capacitance sensor gives an output in volumetric water content (mm of water per 100 mm of soil measured). This is converted from a scaled frequency reading using a default calibration equation, which is based on data obtained from numerous scientific studies in a range of soil textures.

Before a Sentek capacitance sensor can be installed in the soil, it must have minimum and maximum values set. This is done using air and water around each sensor (lecture limits of the volumetric water content – dry and saturated, respectively).

Soil moisture was monitored in the study area at regular intervals of 1 h to a depth 3.0 meters during 2016 using two EnviroScan™ (Campbell Scientific, 2016) probes installed next of the borehole SD-03 (Figure 2). Every EnviroScan™ probes included six capacitance sensors that allowed the determination of soil moisture every 0.5 meter, thus is, at the depths of 0.5, 1.0, until 3.0 m deep. This distribution of depths allowed to monitoring moisture variations for those soil layers which are relevant to this study: landfill, residual soil and saprolith. Sensor calibration was based on the relationship provided by the manufactured (Campbell Scientific, 2016) based on dry and wet readings of each sensor.

2.3 Geotechnical survey

SPT (Standard Penetration Test) boreholes and soil sample collections were performed at six (06) locations along the slope (SD-01 to SD-6) along three different profiles (Figure 3). Disturbed and undisturbed samples were taken under different geotechnical conditions for stability analysis of three (3) critical profiles of the study area (A-A'; B-B'; C-C').

Three (03) undisturbed samples were collected in migmatitic saprolith block close to the SD-04 borehole. This material occurs anisotropically and discontinuously, because it presents significant textural variation resulting from the heterogeneity of the parental rock, being predominantly formed by silt and fine sand, with variable occurrence of clay. From the 6 boreholes (SD-1 to SD-6) and the 3 undisturbed blocks it was possible to obtain a total of 12 soil samples to perform geotechnical characterization tests of the study area following Brazilian standard procedure.

Disturbed and undisturbed samples collected were used to perform grain size analysis test (ABNT, 1984b and 1995), soil particle density (ABNT, 1984a), bulk density, specific dry mass and Atterberg limits (ABNT, 1984c and 1984d). Parameters of effective cohesion (c') and effective friction angle (ϕ') were obtained from saturated direct shear tests, using square shaped undisturbed samples with 60 mm of side and height of 25 mm. The soil samples were in their natural state, being representative of the "Residual" and "Saprolith" soil layers. All samples were saturated and subjected to net normal stress of 25, 50 and 100 kPa applied during 24h with a constant velocity of 0.033 mm/min. The vertical displacements were recorded during this period and after stabilization.

Water retention curves -WRC of the residual soils layers were obtained using pressure plate for suctions <100 kPa and filter paper for suctions ≥ 100 kPa. Samples were initially saturated for 12 hours. The saturated hydraulic conductivity - Ksat was obtained in laboratory using a constant head permeameter. Hydraulic conductivity functions were estimated from the WRC, Ksat using the Van Genuchten (1980) model. In the case of landfill deposits, the values of Ksat for different soil texture were those obtained Ahrendt (2005) from core measurements.

2.4 Modelling experiments

Physical-based hydrological models have been widely applied to predict the development of pore-pressure due to the infiltration in shallow landslides (Frattini et al., 2009; Iverson, 2000). Generally, soils with high permeability become unstable under saturated conditions, while soils with low permeability may destabilize even in unsaturated conditions due to the decrease of the shear strength caused by low soil matrix suction. Several models, based on the infinite slope concepts, that integrates hillslope hydrology with slope stability are reported in literature, for instance CHASM (Anderson and Lloyd, 1991), SHALSTAB (Dietrich et al., 1998), TRIGRS (Baum et al., 2002) and GEOtop-FS (Rigon et al., 2006).

GeoStudio (2012) is another coupled hydrological slope stability model, in which SEEP/W and SLOPE/W plugins are used to simulate the instability of slopes during extreme rainfalls, which were the software package used in this study. Several previous studies have studied the effect of infiltration on rainfall-induced landslides using those plugins (for instance Ng and Shi, 1998; Gasmo et al., 2000; Kim et al., 2004; Huat et al., 2006; Oh and Vanapalli, 2010; Acharya et al., 2016). In this study, the versatility of GeoStudio (2012) for handling boundary conditions allowed to simulate several scenarios involving natural conditions and anthropic factors separately.

The modelling of the stability and seepage analysis was divided in two parts: (1) transient unsaturated seepage analysis; (2) stability analyses coupled with the results from the previous step.

For the seepage analysis, 35-days accumulated rainfall of the period 01/12/1999 through 04/01/2000 was considered, since that event triggered several landslides in the study area (Ahrendt and Zuquette, 2003). In addition to the geotechnical parameters, anthropic factors that induce landslides typical of Brazilian urban slopes, specifically housing load, man-made cuts and leakage from pipes, were included in the modelling experiment with the aim of analysing the degree of influence of these factors on the trigger of landslides in the study area during 2000 (Figures 3 and 4).

The boundary conditions were set according to field observations on the landslide area (Figure 4) and boundary conditions used by Rahardjo et al. (2007). The non-saturated transient flux results were obtained for two cases: considering only the accumulated rainfall and rainfall including linear leakage along the cut slope. The initial pore-pressure values used in the transient flow analysis were obtained indirectly from the WRC and the data of the Soil moisture sensors installed in the study area (Figures 6 and 7).

Next, the factor of safety (FS) for the slope was estimated from the transient seepage modelling coupled with the stability analysis tool (Geo-Slope, 2012a). All the stability analyses were conducted considering the theory of static equilibrium of forces and momentum. The FS were calculated using the geotechnical and anthropic parameters, obtained from the method of Morgenstern-Price, which considers circular and non-circular rupture surfaces.

3 Results

3.1 Geotechnical survey

The result of the granulometric analyses of the residual and saprolith layers of the three profiles studied are presented in Figure 4. Residual layer (sample SD-01/2.0m) can be classified as sandy loam, with percentage of sand and silt of 53 % and 25 % respectively.

The soil samples representative of the saprolith layer showed a significant variation of the percentage of the clay fraction (3 to 24%), silt (14 to 42%) and sand (53 to 73%), indicating that soil profiles are heterogeneous, which in agreement with the textural characteristics of its parent material (migmatitic gneiss). Therefore, it is expected that the mechanical and hydraulic properties of this soil layer is also heterogeneous. The general results of the geotechnical tests (general characteristics, shear strength and saturated hydraulic conductivity) of the samples of the representative soils of the studied area are presented in Table 2.

Analysing the values of the effective resistance parameters (c' and ϕ') and saturated hydraulic conductivity (Table 2), the values representative of the 'Saprolith' layer showed significant variability: the coefficient of variation was 85% for the effective cohesion; 20% for the effective friction angle, and 89% for the saturated hydraulic conductivity, reflecting the heterogeneity character of the parent material. The values of the resistance and Ksat parameters obtained in this study are comparable to other mean reference values of residual gneiss soils representative of other Brazil (Costa Filho and Campos, 1991; Ahrendt, 2005; Reis et al., 2011).

Figure 5 shows the water retention curves of the soil layers representative of the profiles. In general, the residual and saprolith layers are able to hold more water compared to the landfill deposit. For example, for a field matrix suction level of 100 kPa, the volumetric moisture values of the Landfill Deposit, Residual Soil and Saprolith layers are, respectively, 0,06 m^3/m^3; 0,24 m^3/m^3; 0,26 m^3/m^3.

3.2 Soil moisture data

Soil moisture data from 2016 from the EnviroScan probes (3G1 and 3G2) are presented in Figure 7. The data from 3G1 (upper graph of Figure 7) showed that the sensor installed at a lower depth (0.5 to 1.0 meter), representative of the landfill deposit (green curve) layer, have variations larger soil moisture variations ($\Delta\theta$ = 32%), with maximum and minimum humidity values recorded in March (46%) and April (14%), respectively. At deeper layers (1-3 meters deep), representative of the "Residual" and "Saprolith" layers (black and red curves), time variation of soil moisture is much lower ($\Delta\theta$ = 10%, on average). In the layer Residual layer (black curve), maximum and minimum values of soil moisture were verified in January (38%) and May (27%), respectively. In the case of the saprolith layer (red curve) maximum and minimum humidity values in the months of June (40%) and May (32%). The different dynamics among the three soil layers are reflecting not only differences in the retention properties of each layer considered but also the deep soil water dynamics down the soil profiles. This explains why the upper layer (landfill deposit) shows a more spiky behaviour in response the rainfall; while the other two layers exhibit gradual and delayed variations related to deep water percolation.

Analysing the data of the probe 3G2 (lower graph of Figure 7), it is clear that the soil moisture variation of the sensor of the surface layer, representative of the Landfill Deposit layer (green curve), was significantly lower ($\Delta\theta$ = 15%) compared to the same layer of probe 3G1. Maximum and minimum soil moisture values were recorded in September (43%) and August (28%), respectively. At deeper depth, within the residual and saprolith layers (black and red curves), time variation of soil moisture variation is similar than the measurements of probe 3G1 ($\Delta\theta$ = 9%, on average). For the "Residual" layer (black curve) maximum and minimum soil moisture values were observed in January (31%) and May (21 %), respectively; while in the "Saprolith" layer (red curve) maximum and minimum soil moisture values in the months of January (37%) and August (30%).

Contrasting differences in the soil moisture behaviour of the landfill deposit from the probes 3G1 and 3G2 clearly indicates that soil parameters variability is much higher in top layer. This was expected considering that this layer is the result of the cut-and-fill processes mixed with construction waste of several types.

3.3 GeoSlope simulations input data

Table 3 summarizes the parameters used in the numerical simulation with GeoSlope software, based on the geotechnical survey and information extracted from different sources.

Regarding the geotechnical properties, in order to reduce the uncertainties due to the heterogeneity of the parent material, the mean values of the resistance (c' and ϕ'), bulk density and saturated hydraulic conductivity parameters for saprolith and residual (Table 2) were used in the flow and stability modelling. As mentioned before, for the landfill deposit, the geotechnical parameters were those obtained by Ahrendt (2005).

Based on the field information from previous studies in Brazil, the anthropic factors considered in the simulations were: point leakage sources of 1.0 m^3day^{-1} (SABESP, 1993 and 2016) for simulation that include leakage; distributed load due to one floor housing of 2.0 kN m^{-2} (ABNT, 1980); height of the cutting slope (based on field data). In the case of the simulations that include leakage, one point of leaking constant value of 1.0 $m^3 day^{-1}$ was considered in the cut slope, after the 10th day of the simulation until the 35st day, since numerical experiments showed that a time interval of 10 days was adequate to minimize the effect of the uncertainties of initial pore-pressure conditions used in the simulations. It should be noted that this strategy help to separate the effect of leakage from other anthropic factors, without impacting the results at the end of the simulation period (day 35).

For the transient flow analysis, the highest average moisture values of the three layers was considered (Landfill deposit - θ_{mean} = 33%, Residual - θ_{mean} = 31%, Saprolith - θ_{mean} = 34%, to November 30, 2016 - light red region in Figure 7). Subsequently, the mean values of humidity were used to obtain the initial values of matrix suction from the representative water retention curves of each layer of the profile. The proper choice of the initial values of matrix suction is to provide the numerical model with a fast and coherent convergence in the pore-pressure distribution of water in the soil layers, aiming to adjust them satisfactorily to the rain data considered in the flow analysis (01 From December 1999 to January 4, 2000 - 35 days).

For the transient flow analysis, the initial conditions of the simulations were derived assuming initial soil moisture values of 0.33 $m^3.m^{-3}$, 0.31 $m^3.m^{-3}$ and 0.34 $m^3.m^{-3}$, for the landfill deposit, residual and saprolith layers respectively. These values correspond to average of the highest soil moisture values of the two probes during November 2016, and indicated by the light-red shaded area of Figure 7.

Subsequently, the mean values of humidity were used to obtain the initial values of matrix suction from the representative water retention curves of each layer of the profile (Figure 6). This choice of the initial values of matrix suction of the numerical experiments proved to be crucial to achieve a fast and coherent convergence of pore-pressure distribution of soil layers in the simulations, since they are representative of the 35 days period considered in the flow analysis (From 01/12/1999 through 04/01/2000). Based on this approach, the values of negative pore pressure (matrix suction) were -10 kPa for landfills, -40 kPa for residual and -40 kPa for the saprolith.

3.4 Factor of safety analysis

Figure 8 shows the time variation of the safety factor (FS) during 35 days for the 2000 rainfall for the three profiles. In Figure 8, two "warning zones" are considered: zone of instability FS <1.0, where the possibility of occurrence of landslides is high; and low stability stable zone, 1.0 <FS <1.5, which indicates a low possibility of landslide occurrence. In this warning zone the Brazilian Association of Technical Standards (ABNT, 1991) established the following conditions for the safety degree of the slope: High (1.3≤FS <1.5); Mean (1.15≤FS <1.3); Low (1.0≤FS <1.15).

For all three profiles analysed, it is clear that the effect of daily rain on the decrease of the FS (green line) was practically insignificant, with FS values above the 1.5 threshold (high safety degree of the slope); indicating very low likelihood of landslides. In the “rainfall only” scenario, the variations in FS values are due to the geotechnical and

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geomorphological characteristics of the analysed profiles only. For the "rainfall only" scenario, the difference between FS values in the three profiles are mainly due to: the surface slope, since the profile AA´ is steeper than CC' which is steeper than BB'; due to differences in the thickness and location of the layers along the slope (Figure 4) and; the water table profile, related to the soil layers.

For the second scenario considered in the analysis of the stability, which includes cut-and-fill effects besides rainfall (red line in Figure 8), it was verified that the effect of terrain cuts caused minor effects in the slope stability. Except for the case of the A-A' profile, which presents the FS condition <1.5 between 32th and 35th day after the beginning of rainfall, FS values were above the 1.5 threshold. However, it is important to note that, in the case of the profile A-A', the decrease of FS was more pronounced than in the other profiles analysed, directly related to the positioning of the cuts considered along the slopes located based on field information. The configuration of the cuts used in this profile favour the wetting of the top soil layer and, consequently affected the whole profile stability.

The third scenario of Figure 8 (black line), where the joint influence of two anthropic factors (cut and leakage) with the rainfall of 2000 was considered, and the variations in FS values are significant. For the profile A-A', FS values remained below the threshold of 1.5; while in the other two profiles FS dropped below 1.5 between the 32th and 35th days of simulations in the case of the B-B' profile, and on day 17th for the C-C' profile. It should be noted that, after the 11th after the beginning of simulation, FS values becomes sensitive to rainfall variability.

In addition, it can be seen in Figure 8 that the profiles B-B' and C-C' showed greater sensitivity to leakages, mainly due to the geological-geotechnical characteristics, and the location of the cuts along the slopes, that favoured the decrease of the matrix suction values and, therefore, induced instability in both profiles. In addition, critical condition, FS <1.0, in profiles A-A' and C-C' are verified between days 32th and 35th after the beginning of simulations, in response to the significant rainfall that occurred at the period.

Finally, in the fourth scenario of Figure 8 (light brown line), when all the anthropic factors (cut, leakage and housing loads) are considered together with the daily rainfall. For most of the time, FS values remained below the threshold of 1.5 in in the A-A' and B-B' profiles, while in the case of the profile C-C´ only after the day 34th of the simulation. The probability of landslides increased significantly (FS <1.0) in all profiles from day 32 of the simulation in response to heavy rainfall at the end of the period. In the case of the profile C-C' (light brown line), the inclusion of housing loads appears to provide more stability to the profile, probably related to the fact that the critical break surface estimated by the numerical model was different from that assumed in the case scenario 3 (black line).

Based on the assessment of the Factor of Security presented in Figure 8, it is clear that the probability of landslides associated to 2000 rainfall on slopes covered with natural vegetation is very low. When considering the influence of rainfall in conjunction with anthropogenic factors, there was a significant decreased in the security factors in all the profile studied, although the effect varied between slopes depending on the geological-geotechnical profile characteristics, geomorphological conditions, water table position and the anthropic conditions, thus is, the positioning of cuts, leakage and housing loads along the slope.

In general, slopes became unstable (FS<1.0) between 32th and 35th after the beginning of simulations when high daily accumulated values were verified. Since most of the landslide occurred on day 32th, it follows that the model successfully predicted the time were the landslides began. However, it should be noted that previous accumulated rainfall values were crucial to create favourable conditions for triggering landslides as shown by Figure 8 after the 30th day from the beginning of simulation.

Santoro et al. (2010) recommended in-situ technical surveys of urban hazardous areas after accumulated 72-hour rainfall equal to 60, 80 and 100 mm (depending on the municipality), in order to identify evidences of the imminence of landslides and to enforce eventual preventive removal of population. It can be seen in Figure 8 that the 72h accumulated rainfall were 35 mm for the day 30 after the beginning of simulation; 35 mm for the day 31; 60 mm for the day 32; 191 mm for the day 33. Thus, critical rainfall thresholds (60-100 mm) were exceeded between 32th and 33th day for the events recorded in the year 2000.

In this period, the FS in the three analyzed profiles presented the lowest values, located exactly between the "low-medium security zone" (1.0 <FS <1.3) and "unstable zone" (FS <1.0), which shows that the "anthropic and natural factors integrated analysis method" proposed in this paper successfully predicted the beginning of landslides. Although the 72h rainfall threshold value proposed by Santoro et al (2010) proved to be valid for the 2000 event, results of the simulation indicated that the rainfall 30 days previous to the landslides was crucial to bring FS values closer to critical levels, indicating that critical value presents limitations on slopes initially drier.

4 Conclusions

The Geo-slope model proved to be an efficient and useful tool to predict the landslide of Campos do Jordão municipality due to the rainfall event of 2000 and allowed to disentangle the effects of cut-and-fill, construction practices and pipe leakage in three representative slopes of the area. The use of numerical models that perform flow and stability analyses considering the simultaneous influence of natural and anthropic variables showed to be accurate for the prediction of occurrences of landslides on urban slopes.

Regarding the rainfall critical values use in early warning system by CEMADEN and the Civil Defense for the Campos do Jordão Municipality, our study showed that, although adequate for the event of 2000, the previous rainfall history played a fundamental role to create conditions favourable to the occurrence of landslides. In other words, the threshold currently used for issue early warning would result in false alarms under initial drier soil conditions.

The results of the stability analyses confirmed the hypothesis that the occurrence of landslides in the study area cannot be attributed solely and exclusively to the rainfall events of the year 2000, despite the significant accumulated values. Therefore, numerical modelling results corroborated the fact that the occurrence of landslides was the combination of natural and anthropic factors, with the decisive influence of the latter, thus is, due to the presence of several cuts along the slope combined with load of constructions and leakage. Clearly, human interventions on natural slopes play a fundamental role in triggering landslides in heavily populated steep slopes surrounding urban areas.

Considering that the pattern of land use and construction used in the simulations is representative of most of the neighborhood of Brazilian urban areas, the methodology used in this paper need to be repeated and verified in other areas in order to establish more accurate critical threshold that trigger landslides. Moreover, since the prone to landslide areas of Campos do Jordão Municipality are not the most populated of Brazil compared, for instance, to the outskirts of several metropolitan areas, it becomes crucial to verify whether a mosaic of site-specific rainfall thresholds is needed in heavily occupied areas, rather a single regional threshold, as suggested by Segoni et al. (2014). In this context, this study demonstrated the using the factor of slope safety is viable for determine more accurate rainfall threshold that trigger landslides, with direct impacts on the credibility of early warning systems, which relies in minimizing false alarms or premature/late warnings.

Although the results of this study have uncertainties mainly associated with the geotechnical parameters used in the flow analysis and slope stability, it is the first comprehensive analysis of the factors responsible for triggering landslide in Brazil that integrates field evidence, anthropic effects, geotechnical data and numerical simulation. Future studies should combine modelling tools with probabilistic analysis to consider a wider range of geological-geotechnical and anthropic parameters in the simulations to be able to reproduce more general conditions that occur in the whole municipality.

Finally, considering that this work have demonstrated that the anthropic factors are the main instability factors in urban slopes, it is essential that urban managers and planners promote public policies and enforce laws that restrict the occupation of landslide susceptible areas. Detailed surveys to identify prone to landslide areas are essential, since many urban areas of Brazil lack zoning of hazardous areas, which is essential to implement regulations. Besides this, educational campaigns regarding the adoption of better construction practices and reducing piping leakage will be helpful in already consolidated occupied areas.

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References

ABNT - Brazilian Association of Technical Standards: Determination of the specific mass, NBR-6508. Rio de Janeiro, 8p, 1984a.

ABNT - Brazilian Association of Technical Standards: Loads for the buildings structures calculation, NBR 6120. Rio de Janeiro, 5p, 1980.

ABNT - Brazilian Association of Technical Standards: Rocks and soils – terminology, NBR-6502. Rio de Janeiro, 1995.

ABNT - Brazilian Association of Technical Standards: Slopes stability, NBR-11682. Rio de Janeiro, 39p, 1991.

ABNT - Brazilian Association of Technical Standards: Soil – determination of the liquid limit, NBR 6459. Rio de Janeiro, 6p, 1984c.

ABNT - Brazilian Association of Technical Standards: Soil – determination of the plastic limit, NBR 7180. Rio de Janeiro, 3p, 1984d.

ABNT - Brazilian Association of Technical Standards: Soil – grain size analysis test, NBR-7181. Rio de Janeiro, 13p, 1984b.

Acharya, K. P., Bhandary, N. P., Dahal, R. K., Yatabe, R.: Seepage and slope stability modelling of rainfall-induced slope failures in topographic hollows, Geomatics, Natural Hazards and Risk, 7(2), 721-746, 2016.

Ahrendt, A. and Zuquette, L. V.: Triggering factors of landslides in Campos do Jordão City, Brazil, Bulletin of Engineering Geology and the Environment, 62, 231-244, 2003.

Ahrendt, A.: Gravitational mass movements - proposal of a forecast system: application at the urban area of Campos do Jordão City-SP, Brazil. (In Portuguese), Doctoral thesis, School of Engineering of São Carlos, São Paulo University, Brazil, 390 pp., 2005.

Anderson, M. G. and Lloyd, D. M.: Using a combined slope hydrology-stability model to develop cut slope design charts. Proc. Inst. Civ. Eng., 2,705-718, 1991.

Andrade, E.: Risk mapping associated to landslides, flood, erosion and undercutting of riverbank in municipality of Campos do Jordão, São Paulo State, Brazil (in Portuguese), IG-CEDEC Technical Report number 01/2013, 4, 2014.

Baum, R. L., Savage, W. Z., and Godt, J. W.: TRIGRS – a FORTRAN program for transient rainfall infiltration and grid-based regional slope stability analysis, US Geological Survey Open File Report 2002-424, 38 pp, 2002.

Beven, K. J. and Kirkby, M. J.: A physically based variable contributing area model of basin hydrology, Hydrological Sciences Bulletin, 24(1), 43-69, 1979.

Burton, A. and Bathurst, J.: Physically based modelling of shallow landslide sediment yield at a catchment scale, Environmental Geology, 35, 89–99, 1998.

Campbell Scientific: EnviroSCAN™ soil water content profile probes, Instruction Manual, 48p, "available at: https://s.campbellsci.com/documents/us/manuals/envirosmart.pdf, 2016."

CEDEC – Civil Defense Coordination of the São Paulo State: databases of the summer operation emergency calls from 2000 through 2013 (in Portuguese), São Paulo, 2013.

Cho, S. E.: Infiltration analysis to evaluate the surficial stability of two-layered slopes considering rainfall characteristics, Engineering Geology, 105, 32-43, 2009.

Coelho Netto, A. L., Avelar, A. S., Vianna, L. G. G., Araújo, I. S., Ferreira, D. L. C., Lima, P. H. M., Silva, A. P. A., and Silva, R. P.: The extreme landslide disaster in Brazil, Landslide Science and Practice, 6, 377-384, 2013.

Costa Filho, L. M. and Campos, T. M. P.: Anisotropy of a gneissic residual soil, in: Proceedings of the 9th Pan-American Conference on Soil Mechanics and Foundations Engineering, Vina Del Mar, Chile, 51-61, 1991.

Crosta, G.: Regionalization of rainfall thresholds: an aid to landslide hazard evaluation, Environ Geol., 35, 131-145, 1998.

D'Orsi, R., D'Ávila, C., Ortigão, J. A. R., Dias, A., Moraes, L., and Santos, M. D.: Rio-Watch: The Rio de Janeiro Landslide Watch System, in: Proceedings of the 2nd Pan-American Symposium on Landslides, Rio de Janeiro, Brazil, 21-30, 1997.

Dietrich, W. E., Asua, R. R., Orr, J. C. B., and Trso, M.: A validation study of the shallow slope stability model, SHALSTAB, in the forest lands of Northern California. Stillwater Ecosystem, Watershed and Riverine Sciences, Berkeley, 59 pp, 1998.

Frattini, P.; Crosta, G., and Sosio, R.: Approaches for defining thresholds and return periods for rainfall-triggered shallow landslides, Hydrol Process., 23, 1444-1460, 2009.

Gasmo, J. M.; Rahardjo, H., and Leong, E. C.: Infiltration effects on stability of a residual soil slope, Computers and Geotechnics, 26, 145-65, 2000.

Geo-Slope: Seepage modeling with SEEP/W: an engineering methodology, User manual, Geo-Slope International, 199p, 2012b.

Geo-Slope: Stability modeling with SLOPE/W: an engineering methodology, User manual, Geo-Slope International, 238p, 2012a.

GeoStudio: GeoStudio Tutorials includes student edition lessons. Calgary, Alberta, Canadian: Geo-Slope International Ltd., 2012.

Guzzetti, F.; Peruccacci, S.; Rossi, M., and Stark, C.P.: Rainfall thresholds for the initiation of landslides in central and southern Europe, Meteorology and Atmospheric Physics, 98, 239-267, 2007.

Huat, B .B. K., Ali, F. H., and Rajoo, R. S. K.: Stability analysis and stability chart for unsaturated residual soil slope, American Journal of Environmental Sciences, 2 (4), 154-160, 2006.

IBGE – Brazilian Institute of Geography and Statistics, social and economic data of the Brazilian citizens (in Portugguese), "available at: http://cidades.ibge.gov.br/painel, 2016."

Iverson, R. M.: Landslide triggering by rain infiltration, Water Resour. Res., 36, 1897-1910, 2000.

Kim, J., Jeong, S., Park, S., and Sharma, J.: Influence of rainfall-induced wetting on the stability of slopes in weathered soils, Engineering Geology ,75, 251-262, 2004.

Lagomarsino, D., Segoni, S., Fanti, R., and Catani, F.: Updating and tuning a regional-scale landslide early warning system, Landslides, 10, 91–97, 2013. DOI: 10.1007/s10346-012-0376-y

Londe, L. R., Coutinho, M. P., Di Gregório, L. T., Santos, L. B. L., and Soriano, E.: Water related disasters in Brazil: perspectives and recommendations (in Portuguese), Ambiente and Sociedade, 17(4), 133-152, 2014.

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

Oh, W.T. and Vanapalli, S.K.: Influence of rain infiltration on the stability of compacted soil slopes, Computers and Geotechnics, 37, 649-657, 2010.

Pack, R. T., Tarboton, D. G., and Goodwin, C. N.: The SINMAP approach to terrain stability mapping, in: Proceedings of the 8th Congress of the International Association of Engineering Geology, Vancouver, Canada, 21-25, 1998.

Rahardjo, H., Ong, T. H., Rezaur, R. B., and Leong, E. C.: Factors controlling instability of homogeneous soil slopes under rainfall, J. Geotech. Geoenviron. Eng., 133 (12), 1532-1543, 2007.

Reis, R.M., Azevedo, R.F., Botelho, B.S., and Vilar, O.M.: Performance of a cubical triaxial apparatus for testing saturated and unsaturated soils, Geotechnical Testing Journal, 34 (3), 1-9, 2011.

Ridente, J. L., Ogura, A. T., Macedo, E. S., Diniz, N. C., Alberto, M. C., and Santos, H. P.: Accidents associated to mass movements that were occurred in municipality of Campos do Jordão, SP, at January 2000: technical actions after the disasters (in Portuguese), IPT publications number 2815, 14p, 2002.

Rigon, R., Bertoldi, G., Over, T. M.: Geotop: a distributed hydrological model with coupled water and energy budgets, Journal of Hydrometeorology, 7(3), 371– 388, 2006.

SABESP: Leak tests, http://site.sabesp.com.br/site/interna/Default.aspx?secaoId=244, Accessed 04 Abril 2016, 2016.

SABESP: Water reduction program not charged, Synthetic report, Sao Paulo: Lyonnaise des Eaux Services Associés – LYSA, 1993.

Santoro, J., Mendes, R. M., Pressinotti, M. M. N. and Manoel, G. R.: Correlation between rainfall and landslides occurred during the operation of the prevention plan of civil defense in State of São Paulo, SP (in Portuguese), in: Proceedings of the 7th Brazilian Symposium on Geotechnical and Geoenvironmental Cartography, Maringá, Paraná, 1-15, 2010.

Segoni, S., Rosi, A., Rossi, G., Catani, F., and Casagli, N.: Analysing the relationship between rainfalls and landslides to define a mosaic of triggering thresholds for regional-scale warning systems, Nat. Hazards Earth Syst. Sci., 14, 2637–2648, doi:10.5194/nhess-14-2637-2014, 2014.

Tatizana, C., Ogura, A. T., Cerri, L. E. S., and Rocha, M. C. M.: Numerical modeling of the analysis of correlation between rainfall and landslides applied to the slopes of the Serra do Mar in municipality of Cubatão (in Portuguese), in: Proceedings of the 2nd Brazilian Congress of Engineering Geology, 237-248, 1987.

Terlien, M. T.: The determination of statistical and deterministic hydrological landslide triggering thresholds, Environ Geol., 35, 124-130, 1998.

Van Asch, T. W. J., Buma, J., and Van Beek, L. P. H.: A view on some hydrological triggering systems in landslides, Geomorphology, 30, 25-32, 1999.

Van Genuchten, M. T.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Journal of the Soil Science Society of America, 44, 892-898, 1980.

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Table 1 – Historical disasters in Campos do Jordao Municipality. Source: Ridente et al. (2002) and Andrade (2014).

Process	Location	Year	Damages	Causes
Mudflow	Vila Albertina	1972	17 fatalities 60 houses buried	Saturated soil (8m thick), loading and vibration due to construction activities
Landslide	Britador, Vila Santo Antonio and Vila Paulista Popular	1991	149 affected 11 houses buried 4 injured	214.5 mm of rainfall in three days
Landslide and Mudflow	Britador, Vila Albertina, Vila Santo Antônio, Vila Nadir Vila Sodipe and Vila Paulista Popular	2000	10 fatalities 1840 affected	453.2 mm in five days

Table 2 – Results of the geotechnical survey of soils of the study areas.

Sample	Depth (m)	Soil layer	USCS	Unit weight (kN/m^3)	Effective cohesion (kPa)	Effective friction angle (°)	Hydraulic conduct. (m/day)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	w_L (%)	w_P (%)	IP (%)
SD-01	2.0	R	SC	18.3	37	56	0.384	10	53	25	12	27	18	9
	4.6	S	SC	19.1	18	37	0.817	0	53	35	12	35	22	13
	6.6	S	SC	17.9	2	49	0.685	0	59	27	14	29	20	9
SD-02	2.6	S	SC	21.4	19	34	0.102	5	50	21	24	28	17	11
	4.6	S	SM	17.5	14	42	0.325	0	73	14	13	33	20	13
SD-03	1.6	S	SM-SC	18.1	22	43	0.454	1	59	29	11	22	15	7
	2.6	S	SM-SC	16.8	2	52		5	55	30	10	23	17	6
SD-05	12.8	S	SC	17.5	48	54	0.053	0	55	33	12	32	21	11
SD-06	7.6	S	SM	17.8	42	28	0.024	1	72	15	12	-	-	-
Block-1	2.0	S	SM	16.0	2	53	0.267	0	72	21	7	-	-	-
Block-2	2.0	S	SM	16.0	49	37	0.081	0	55	42	3	-	-	-
Block-3	3.0	S	SM	16.0	13	46	0.258	0	58	28	14	-	-	-

Residual soil (R); Saprolith (S).

Table 3 – Geotechnical and anthropic parameters used on unsaturated seepage and stability analysis

Geotechnical										Anthropic		
Profile	Slope declivity (°)	Slope height (m)	Soil layers	Shear strength effective parameters#	Unit weight (kN m^{-2})#	Rainfall (m day^{-1})	Ksat (m day^{-1})	Matric suction (kPa)	Level of the water table	Load in the slope (kNm^{-2})	Height of the cut slope (m)	Leaking in the slope (m^{3}day^{-1})
A - A'	11 - 40	130										
			Fill Deposit	c' = 2 kPa ϕ' = 31º	14,9		0,8208	-7				
B - B'	16 - 33	95	Residual	c' = 15 kPa ϕ' = 36º	18,3	Rainfall events of the 2000 year	0,3840	-40	Data of SPT	2.0	6.0	1.0
			Saprolith	c' = 21 kPa ϕ' = 43º	19,1		0,4694	-40				
C - C'	15 - 35	87										

Fill Deposit (geotechnical parameters from Ahrendt, 2005)

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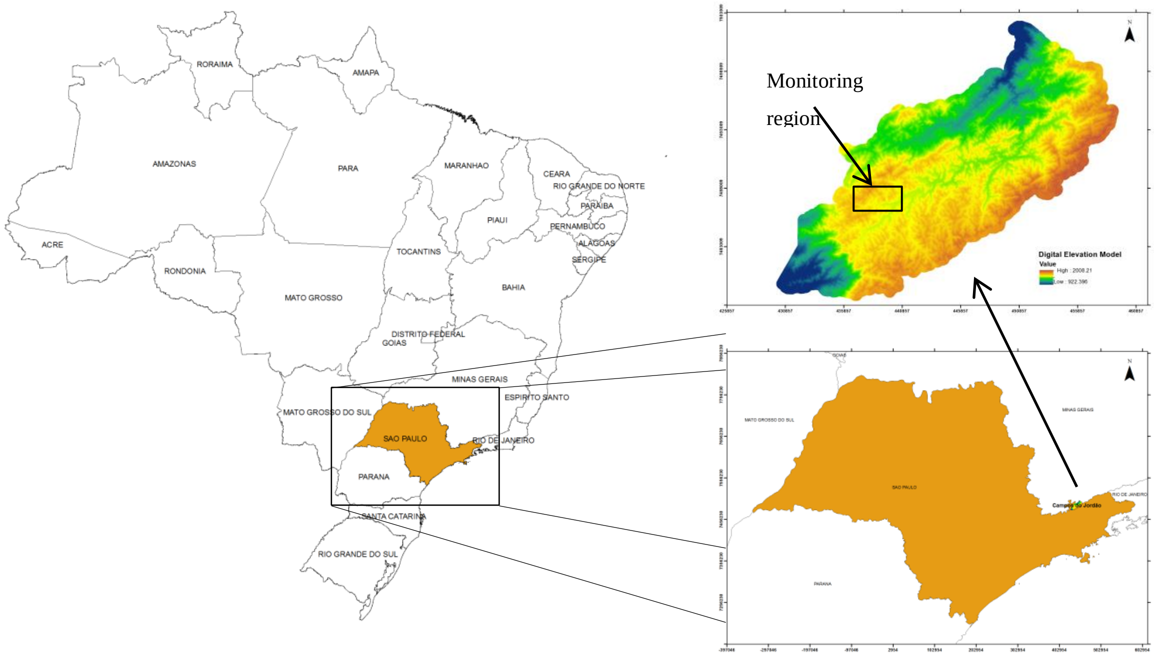

Figure 1. Geographical location of Campos do Jordao municipality and an inset of the study site.

Figure 2. Landslides typology that happened in 2000 on the study site (Source: Ridente et al., 2002).

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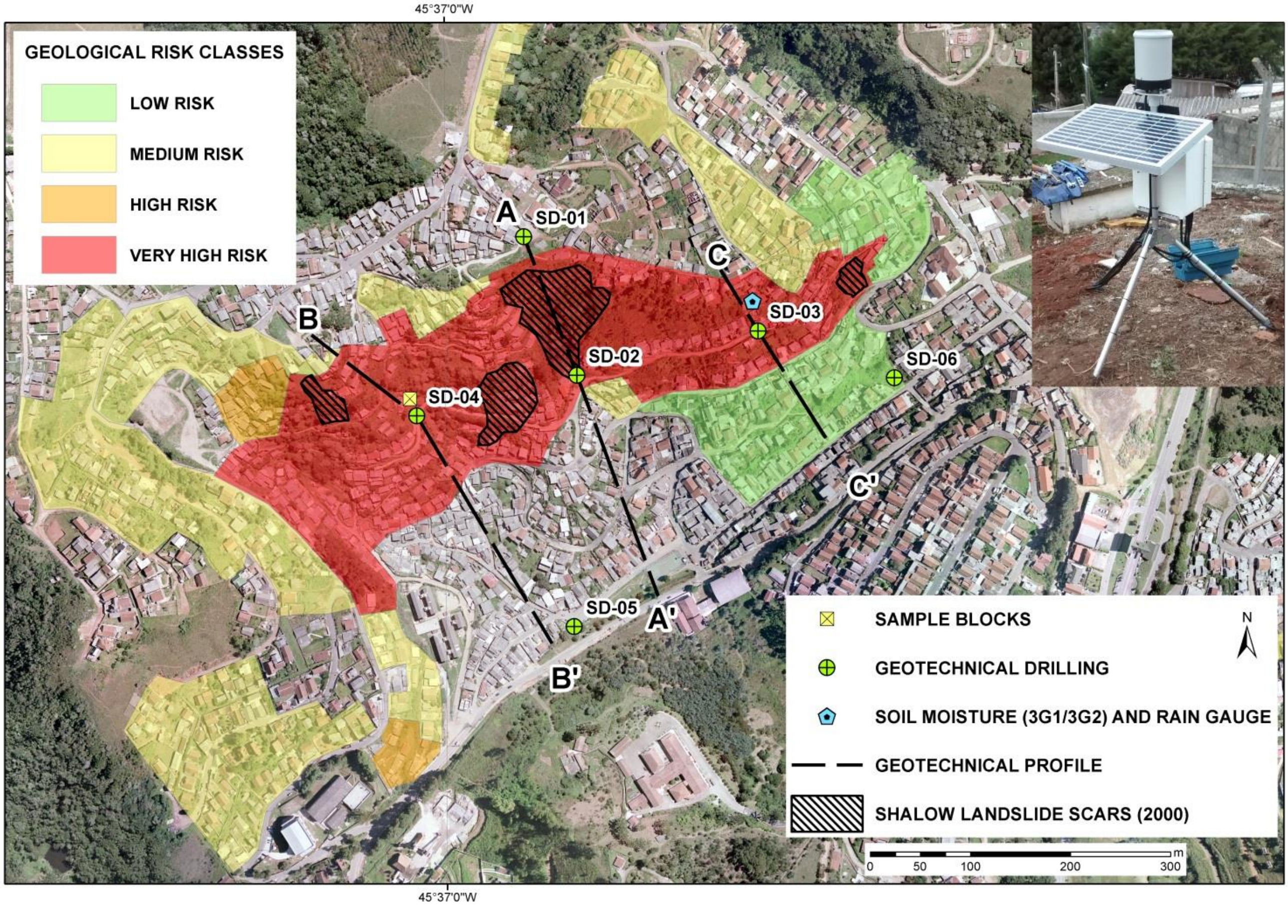

Figure 3. Satellite image of the study site showing the location of monitoring instruments (symbols), geotechnical transects (dotted lines along the slopes); landslide susceptibility areas indicating the level of risk (areas shaded in yellow, orange and red); scars of previous shallow landslides (black cross-hatched area) and deposits of landslides events (blue cross-hatched areas).

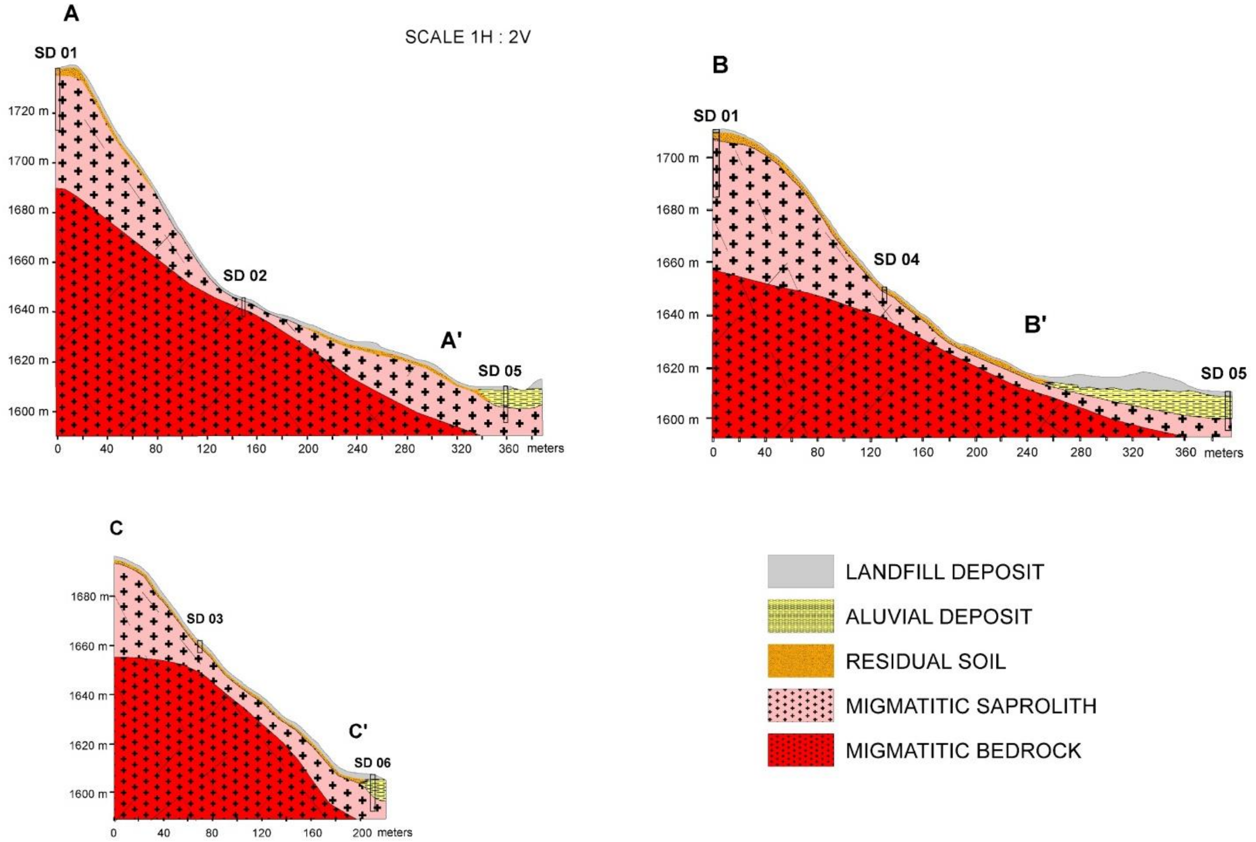

Figure 4. Geological-geotechnical profiles of the study area derived from the geotechnical survey.

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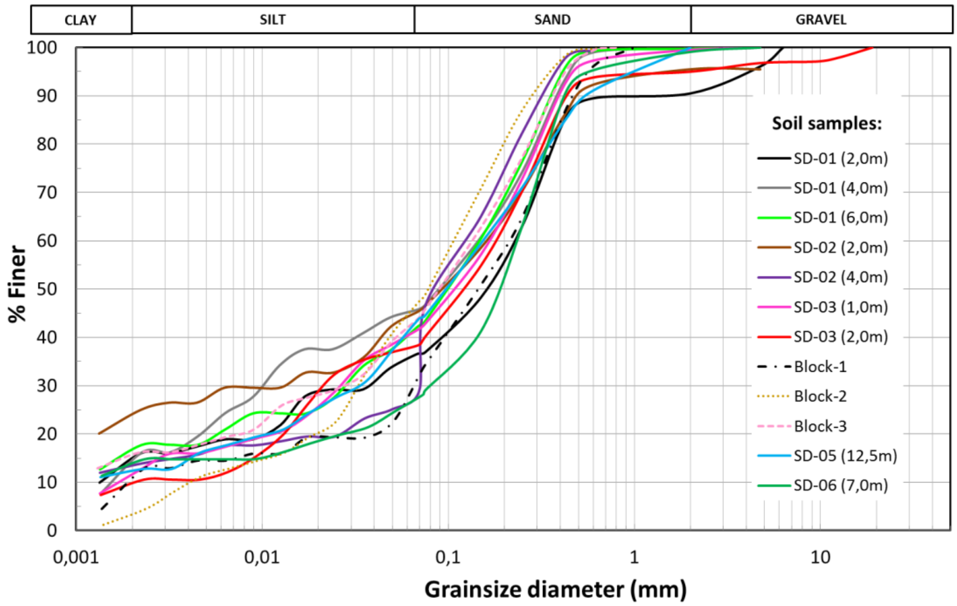

Figure 5. Granulometric distribution for the residual soil and the saprolith of the six boreholes analysed (SD-01 to SD-06) and for the undisturbed soil cores (Block-1 to Block-3).

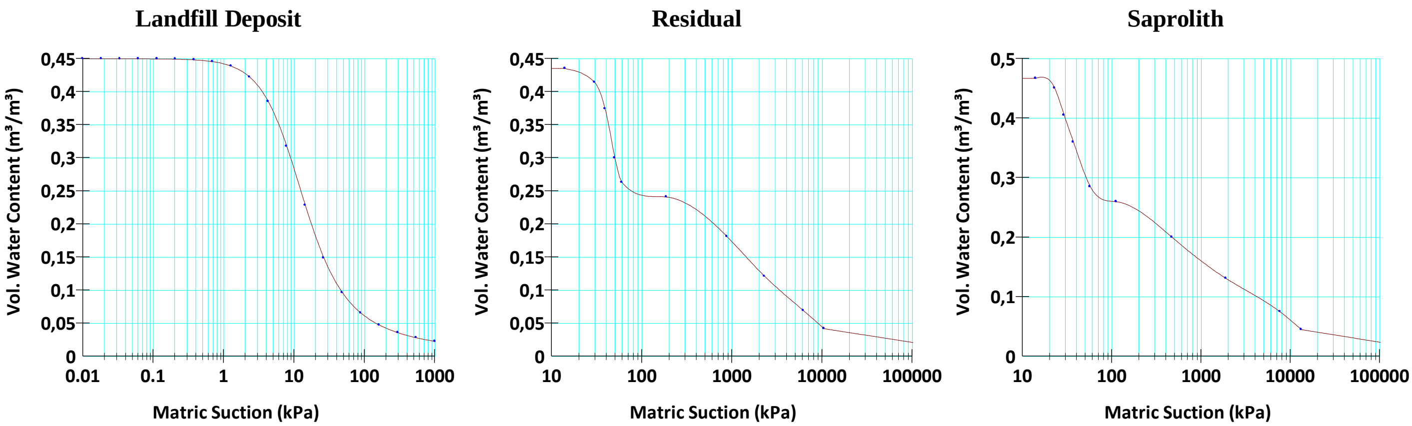

Figure 6. Water retention curves of the three soil types used in transient seepage analysis.

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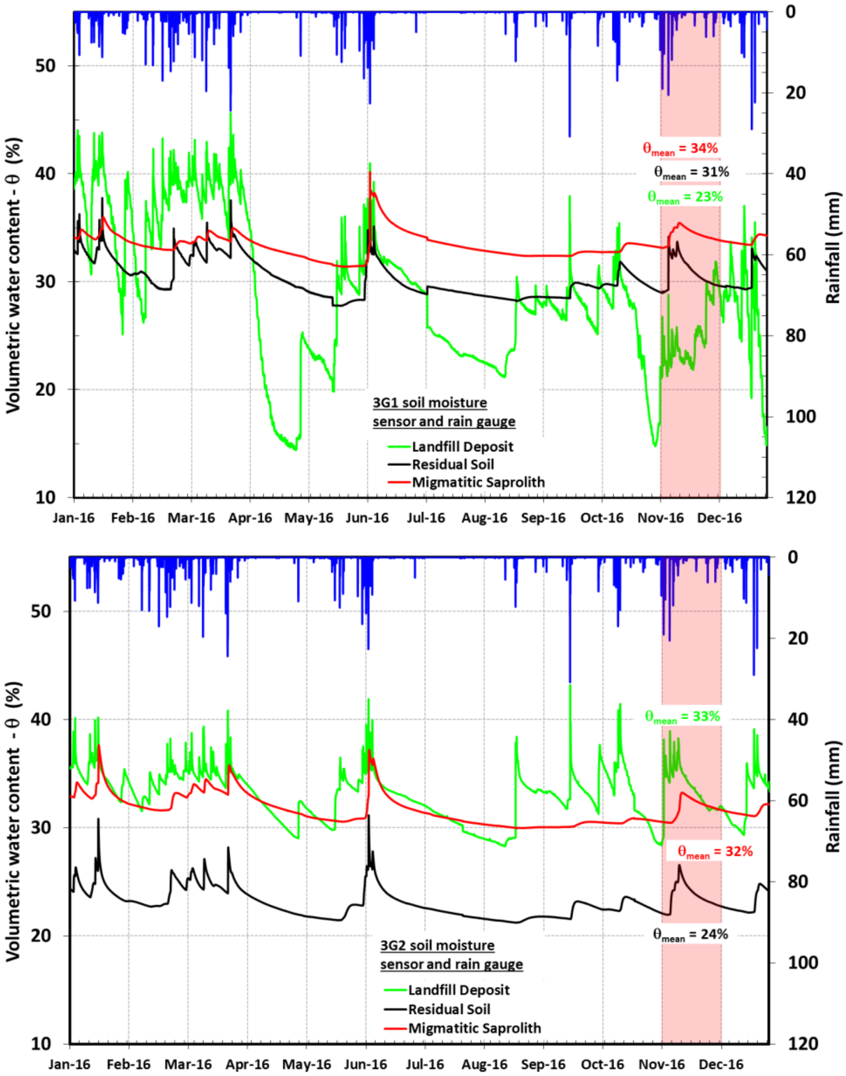

Figure 7. Time variation of soil moisture at different depths during 2016 in the study area in the sensor 3G1 (upper graph) and 3G2 (bottom graph).

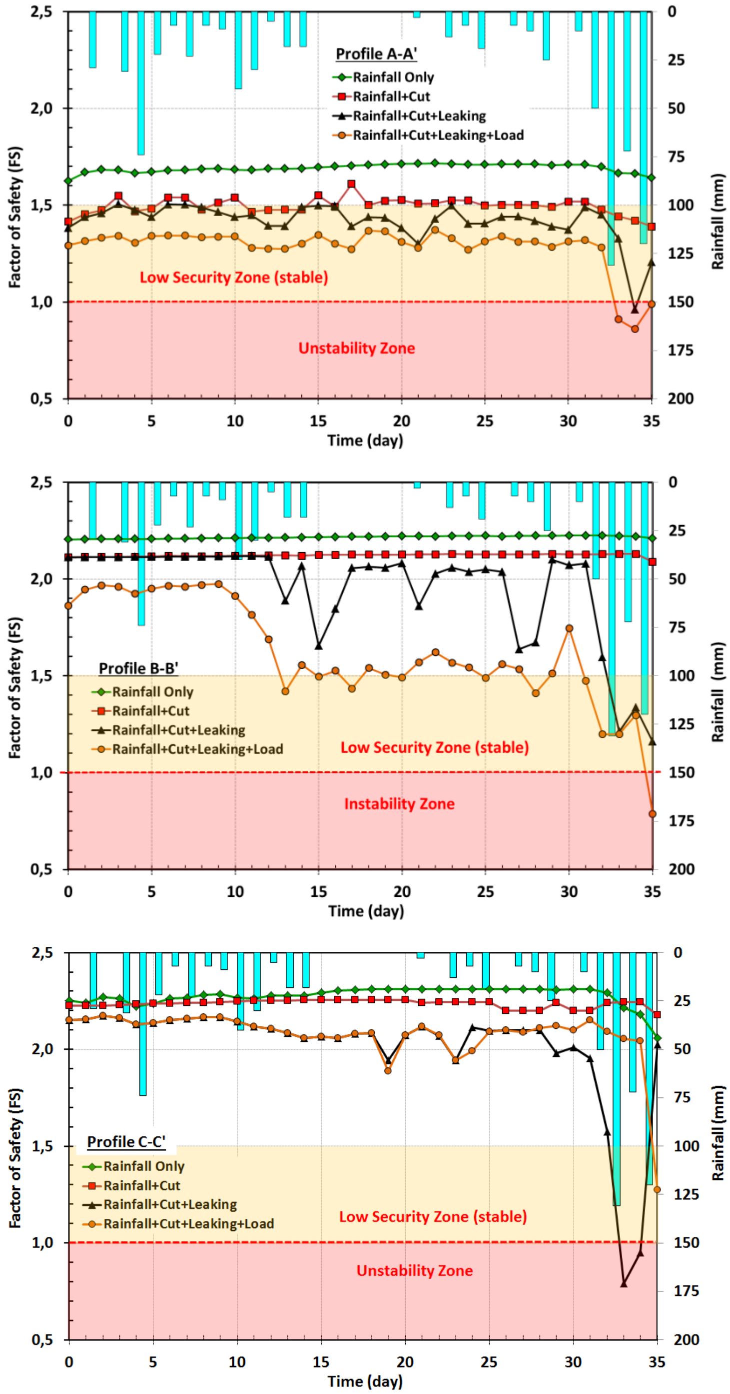

Figure 8. Time variation of the factor of safety for natural conditions and taken into account the additional effects introduced by anthropic disturbances on profiles A-A', B-B' and C-C'.