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

Rodolfo M. Mendes, Márcio Roberto M. de Andrade, Javier Tomasella, Márcio Augusto E. de Moraes, and Graziela B. Scofield

National Center for Monitoring and Early Warning of Natural Disasters, Parque Tecnológico/São José dos Campos, Estrada Doutor Altino Bondesan 500,12247-016, São Paulo, Brazil

Correspondence: Rodolfo M. Mendes (rodolfo.mendes@cemaden.gov.br)

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Abstract. Located in a mountainous area of south-eastern Brazil, the municipality of Campos do Jordão has been hit by several landslides in recent history. Among those events, the landslides of early 2000 were significant in terms of the number of deaths (10), the population affected and the destruction of infrastructure that was caused. The purpose of this study is to assess the relative contribution of natural and human factors to 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 experiments with GEO-SLOPE software was designed, including separate natural and anthropic factors. Results showed that natural factors, that is, high-intensity rainfall and geotechnical conditions, were not severe enough to trigger landslides in the study area and that human disturbance was entirely responsible for the landslide events of 2000. Since the anthropic effects used in the simulations are typical of hazardous urban areas in Brazil, 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, high-intensity, heavy rain on landscapes dominated by narrow valleys and steep slopes, large areas of the south-eastern and southern Brazil are naturally susceptible to landslides. In addition, recent studies by CEPED (2012) indicate that more than 160 million inhabitants live in urban areas (about 90 % of Brazilian population), and that increased urbanization in cities without urban planning and consequent occupation of hazardous areas have led to an increase in this natural disaster. Consequently, landslides are directly associated with the loss of lives, property and infrastructure damage, and environmental destruction. During 2011, for instance, mountainous regions of the Rio de Janeiro state suffered several landslides that caused more than 1500 deaths and severe damage to urban and rural infrastructure (Coelho Netto et al., 2013).

In spite of floods (generally gradual flooding) being the most disruptive natural disaster in terms of economic damages and population affected, landslides have been considered the most severe in terms of death toll (Londe et al., 2014). Although landslide and flash floods usually affect heavily urbanized downtown areas, it is also recognized that poor people 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 vegetation. In addition, because of the lack of collection systems, sewage is disposed into the hillslope soils, further increasing the risk of triggering landslides as well as the health risks associated with the lack of sanitation.

Among those areas affected by landslides in SE Brazil, the municipality of Campos do Jordão has been hit by several events since the 1970s. The most recent 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 systems used by the civil defence in Campos do Jordão and by CEMADEN (National Center for Monitoring and Early Warning of Natural Disasters) 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 07:00 local time using manual rain gauges, and the threshold value for triggering landslides was 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 level proposed in previous studies (Tatizana et al., 1987), it was not possible to conduct a 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 to the occurrence of landslides and rainfall conditions. Guzzetti et al. (2007) proposed covering regional thresholds for areas of a few to thousands of square kilometres which have the same meteorological, climatic and physiographic characteristics, whereas for local conditions the geomorphology and climate regime are considered to be applicable to areas in the order of hundreds of square kilometres.

After the event of 2000, new critical 72 h rainfall thresholds values for landslides were proposed for the area. In addition, the civil defence of the state of São Paulo established new critical rainfall amounts for visually monitoring critical areas in order to detect early signals on the imminence of a landslide. However, the peak rainfall intensities recorded in the event of 2000 have not been repeated since, while irregular occupations continued in many landslide-prone areas. Therefore, a detailed study of the event of 2000 is relevant, not only because of its extreme characteristics but also with the perspective that memory of the 2000 event has faded and its impacts are 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 from historical landslide events in the municipality of Campos do Jordão, the aim of this study was to understand the factors responsible for triggering the landslides of early 2000 in the area using a numerical model that fully coupled slope stability analysis with saturated/unsaturated transient pore-water pressure simulations.

Physically based hydrological models have been widely applied to predict pore-pressure build-up due to infiltration in shallow landslides (Frattini et al., 2009; Iverson, 2000). Several models based on the infinite slope concepts that integrate hillslope hydrology with slope stability are reported in the literature, for instance SINMAP (Pack et al., 1998), SHALSTAB (Dietrich et al., 1998), TRIGRS (Baum et al., 2002) and GEOtop FS (Rigon et al., 2006).

During the last decade, physically based landslide prediction models have also been successfully used in early warning systems. Models used in such applications include, among others, the Combined Hydrology and Stability Model (CHASM; Thiebes et al., 2014), the High Resolution Slope Stability Simulator (HIRESS; Rossi et al., 2013); the SLope-Infiltration Distributed Equilibrium (SLIDE; Liao et al., 2010; Montrasio and Valentino, 2008), the Shallow Landslides Instability Prediction (SLIP; Montrasio, 2000; Montrasio et al., 2011). Another slope stability model is the modular software package GeoStudio (2012), in which SEEP/W and SLOPE/W plugins are used to simulate the instability of slopes during extreme rainfall events. Although GEO-SLOPE is a simplified "single slope" model, it has been used in several previous studies to understand the effect of infiltration on rainfall-induced landslides (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), producing very good results (Tofani et al., 2006).

In this study, we analysed several scenarios that included the relative influence of natural and anthropic factors that prevail in the area and identified the most critical factors responsible for the severe landslides of 2000 using the GeoStudio (2012) software due to its versatility in handling separate natural and anthropic boundary conditions.

In addition, we analysed whether the threshold rainfall values established by the civil defence are adequate for early warnings of landslide occurrence, taking into account today's patterns of landslide-prone areas.

2 Material and methods

2.1 Study site

The study site is the municipality of Campos do Jordão in the state of São Paulo, located in a mountainous region along the Mantiqueira Mountains (Fig. 1). In geological and geomorphological terms, the Campos do Jordão plateau is a crystalline plateau block with elevations of more than 2000 m above sea level and bordered by steep cliffs that rise approximately 1500 m over the adjacent Paraíba valley (Almeida, 1976). The relief, strongly conditioned by the structures and lithology of the area, is characterized by the presence of high hills and erosive depressions. On the basis of these amphitheatres peat depressions occur (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 sensi-

Table 1. Historical disasters in Campos do Jordão municipality. Source: Ridente et al. (2002) and Andrade (2014).

Process	Location	Year	Damages	Causes
Earthflow	Vila Albertina	1972	17 fatalities 60 houses buried	Saturated soil (8 m 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 3 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 5 days

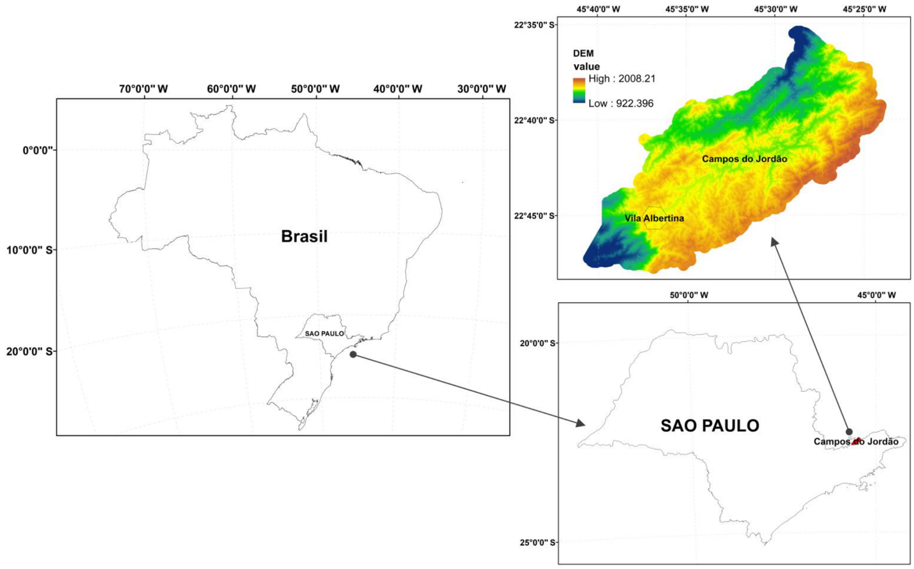


Figure 1. Geographical location of the Campos do Jordão municipality and an inset of the study site.

tive behaviour 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 Jordão (Ogura et al., 2004).

The area where Campos do Jordão is located was occupied by Portuguese settlers during the 18th century. During the hygienist movement (late 19th and early 20th centuries), various health facilities were established in the town, mainly for tuberculosis treatment. Since 1940, the town has experienced a large population growth and urban expansion due to the development of tourism: the number of inhabitants increased from 13 000 in 1950 to more than 50 000 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, especially from the 1970s, of areas with unfavourable geotechnical characteristics, has been pointed out as responsible for most of the natural disasters in Campos do Jordão (Ridente et al., 2002). Table 1 shows the most important events in terms of dead toll and damages recorded in the area.

Landslides in the study area are classified as shallow and translational, with depths of the rupture surfaces less than 2 m. Depending on the position of the rupture, three different processes are observed: the rupture surface occurs in the residual soil of undisturbed ground, the rupture surface occurs in the residual soil of a slope cut, and the rupture surface occurs at the base of the landfill deposit or in the slope residual soil with mobilization of the overlying landfill. The last landslide types are more harmful since they mobilized larger amounts of material. In the case of the event of 2000 (Fig. 2), which is the focus of this study, rainfall began on 31 December 1999 and continued almost uninterrupted for 4 days with high-intensity rainfall bursts. According to the Brazilian Center for Weather Forecasting and Climate Studies (CPTEC), daily rainfall from 31 December 1999 to 5 January 2000 was 78.5, 101, 120, 60, 144.5 and 10.5 mm

Figure 2. Shallow landslides that happened in 2000 at the study site (Source: Ridente et al., 2002).

(Ridente et al., 2002). Landslides associated with this event were considered to be one of the most severe in urban areas in Brazil, since hundreds of landslides occurred, mostly in slopes in poor neighbourhoods where houses are constructed over cut-and-fill areas.

Based on the landslide 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 3 days of about 200 mm of rain, with 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 over 3 days (60, 80 and 100 mm) as critical thresholds for warning levels (Santoro et al., 2010). These thresholds were based on the studies carried out by Tatizana et al. (1987) and have been considered critical for issuing early warnings based on rainfall observation and forecasting.

With the aim 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 the Serra do Mar in the municipality of Cubatão, and by D'Orsi (1997) for the Mantiqueira Mountains in the municipality of Rio de Janeiro. Results showed that the occurrences of Campos do Jordão were below the critical levels of those areas, indicating that the rainfall intensities required for triggering landslides in Campos do Jordão are much lower than the other sites. Therefore, the study of Ahrendt (2005) concluded that rainfall characteristics that trigger landslides in Campos do Jordão are very unique, and a different and more detailed approach was needed.

Considering the limited historical data on landslide occurrence and the few previous studies in the area, it is extremely difficult to define accurate critical threshold rainfall values that trigger landslides, in particular, the effects of 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 in the summer of 2012. Most of the occurrences were observed in cut-and-fill slopes, with evident contribution of waste water and microdrainage deficiency. In recent history occurrences of great magnitude were not recorded; however, the destruction of houses or even the prohibition of occupying damaged houses is a recurring problem.

2.2 Soil moisture monitoring

Soil moisture was monitored hourly to a depth of 3 m over 12 months (1 January 2016 to 31 December 2016), using two EnviroScan™ probes installed next to the borehole SD-03 (Fig. 3). EnviroScan™ probes are installed in customized access tubes manufactured by Sentek Pty. Ltd. Inside the EnviroScan™ probe six Sentek capacitance sensors were distributed. The capacitance sensor gives an output in volumetric water content (millimetres 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

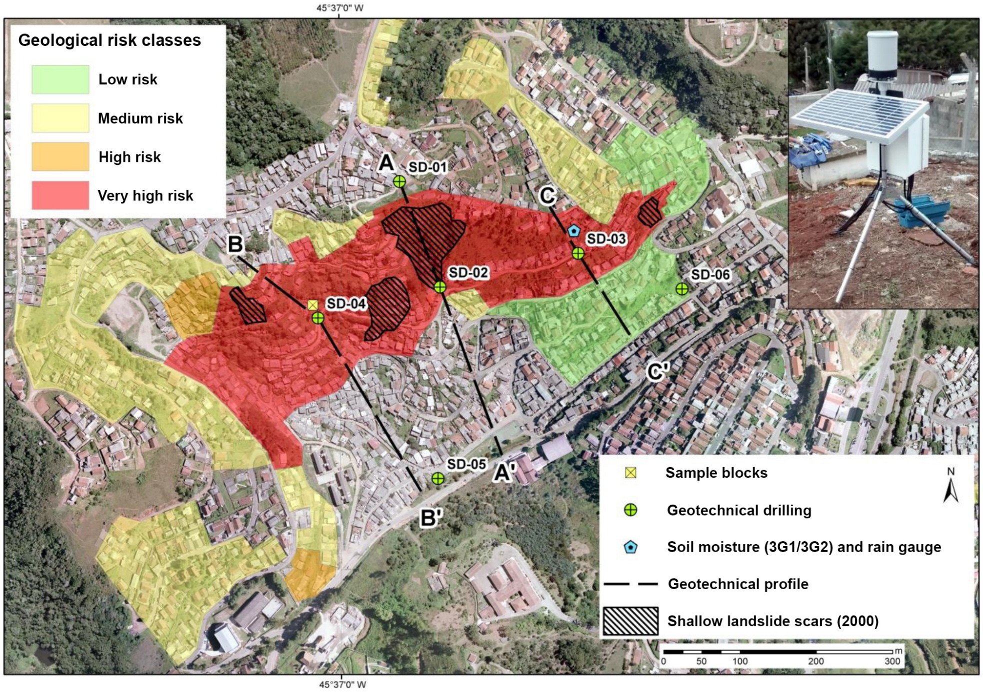


Figure 3. Satellite image of the study site showing the location of monitoring instruments (symbols), geotechnical transects (dotted lines along the slopes), landslide susceptibility areas indicating the level of risk (areas shaded in yellow, orange and red) and scars of previous shallow landslides (black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

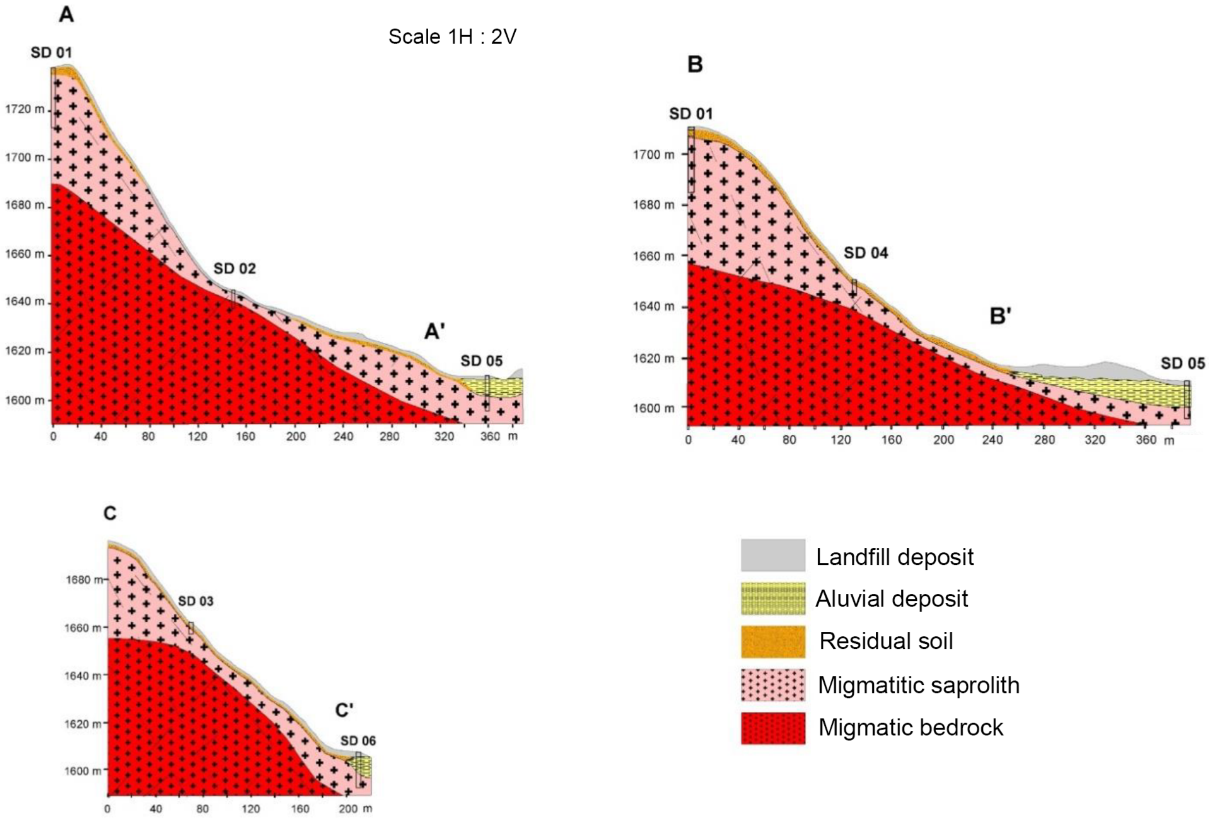


Figure 4. Geological–geotechnical profiles of the study area derived from the geotechnical survey.

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).

Soil moisture was monitored during 2016 at hourly intervals and to a depth of 3.0 m using two EnviroScanTM (Campbell Scientific, 2016) probes installed next to the borehole SD-03 (Fig. 2). Each probe included six capacitance sensors that measured soil moisture every 0.5 m, that is, at the depths of 0.5, 1.0, and 3.0 m, which allowed moisture variations of the landfill, residual and saprolite layers to be monitored. Before the EnviroScanTM capacitance probes were installed in the soil, maximum and minimum values were normalized by matching the raw readings from each sensor at both 0 % (held in air) and 100 % water levels (submerged in water).

2.3 Geotechnical survey

SPT (standard penetration test) boreholes were drilled along three profiles of the study site (A–A', B–B', C–C' in Fig. 3) at six different positions along the slopes (SD-01 to SD-6; Fig. 4). Disturbed and undisturbed samples were taken from the boreholes for the determination of the parameters used for stability analysis.

Three undisturbed samples were collected in migmatitic saprolite 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 six boreholes (SD-1 to SD-6) and the three 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 a grain size analysis test (ABNT, 1984b, 1995), soil particle density (ABNT, 1984a), bulk density, specific dry mass and Atterberg limits (ABNT, 1984c, d). 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 width and height of 25 mm. The soil samples were in their natural state, being representative of the residual and saprolite soil layers. During the consolidation step, all specimens were saturated for 24 h and subjected to net normal stresses of 25, 50 and 100 kPa. Then, in the shearing phase, a constant velocity of 0.033 mm min^{-1} was applied. Vertical and horizontal displacements were recorded during the consolidation and shearing phases.

After saturation of soil samples for 12 h, water retention curves (WRCs) of the residual soils layers were obtained using a pressure plate for suctions < 100 kPa and filter paper for suctions ≥ 100 kPa for the drying path of the samples following the recommendation of Marinho and Oliveira (2006). Results showed that the differences in water retention values at the transition between the methods were not significant, making further adjustments unnecessary (Fig. 8). The saturated hydraulic conductivity (Ksat) was obtained in the 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 textures were those obtained by Ahrendt (2005) from core measurements.

2.4 Modelling experiments

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

For the seepage analysis, 35 days of accumulated rainfall for the period 1 December 1999 to 4 January 2000 was considered, since the 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 occurrence of landslides in the study area during 2000 (Figs. 4, 5 and 6).

The boundary conditions were set according to field observations on the landslide area and the 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 with linear leakage along the cut slope (Fig. 5). The initial pore-pressure values used in the transient flow analysis were obtained indirectly from the WRC and the data on the soil moisture sensors installed in the study area (Figs. 7 and 8). 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 FSs were calculated using the geotechnical and anthropic parameters, obtained from the method of Morgenstern-Price, which considers circular and non-circular rupture surfaces. All the simulations allowed the slope stability module SLOPE/W to identify the most critical rupture surface (Fig. 6). Therefore, the values of the slope safety factor (FS) were the lowest of all conditions analysed.

3 Results

3.1 Geotechnical survey

The results of the granulometric analyses of the residual and saprolite layers of the three profiles studied are presented in

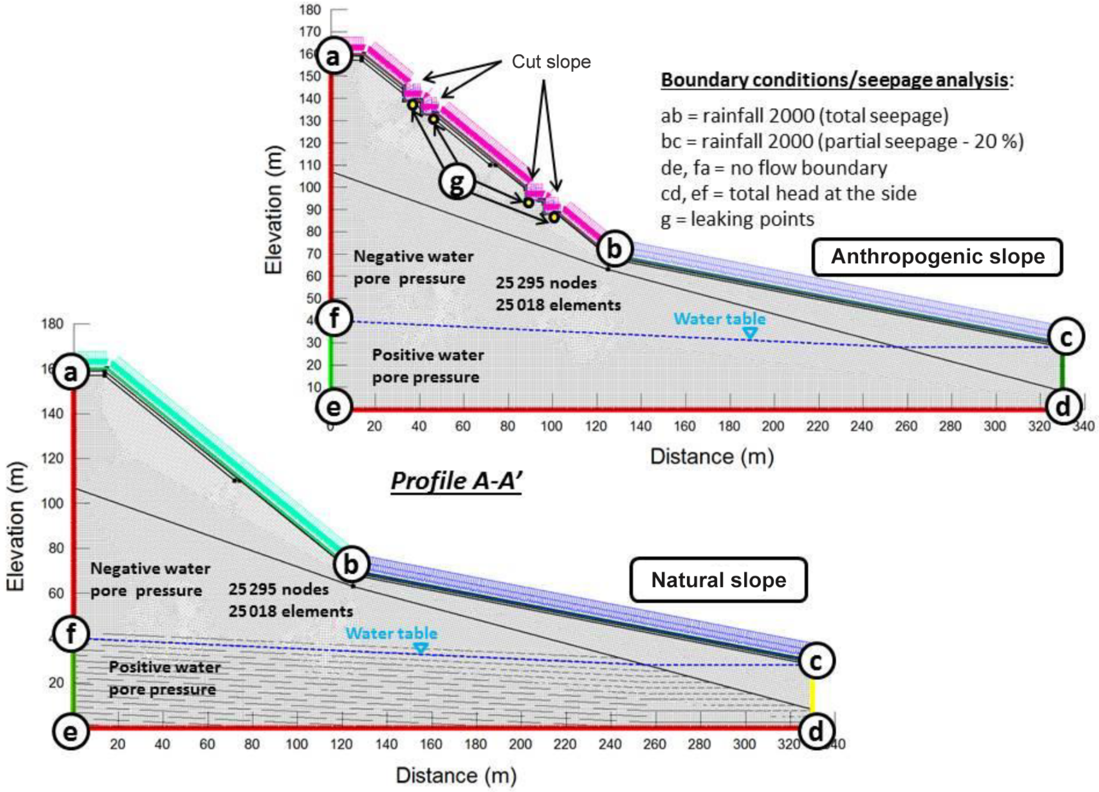


Figure 5. Slope geometry and boundary conditions used in the unsaturated transient seepage analysis with natural and anthropogenic factors (rainfall, cut slope and leakage).

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 s^{-1})	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	w_L (%)	w_P (%)	IP (%)
SD-01	2.0	R	SC	18.3	37	56	4.44×10^{-6}	10	53	25	12	27	18	9
	4.6	S	SC	19.1	18	37	9.46×10^{-6}	0	53	35	12	35	22	13
	6.6	S	SC	17.9	2	49	7.93×10^{-6}	0	59	27	14	29	20	9
SD-02	2.6	S	SC	21.4	19	34	1.18×10^{-6}	5	50	21	24	28	17	11
	4.6	S	SM	17.5	14	42	3.76×10^{-6}	0	73	14	13	33	20	13
SD-03	1.6	S	SM-SC	18.1	22	43	5.25×10^{-6}	1	59	29	11	22	15	7
	2.6	S	SM-SC	16.8	2	52	6.13×10^{-7}	5	55	30	10	23	17	6
SD-05	12.8	S	SC	17.5	48	54	2.77×10^{-7}	0	55	33	12	32	21	11
SD-06	7.6	S	SM	17.8	42	28	3.09×10^{-6}	1	72	15	12	-	-	-
Block 1	2.0	S	SM	16.0	2	53	9.37×10^{-7}	0	72	21	7	–	–	–
Block 2	2.0	S	SM	16.0	49	37	2.98×10^{-6}	0	55	42	3	–	–	–
Block 3	3.0	S	SM	16.0	13	46	4.44×10^{-6}	0	58	28	14	–	–	–

* Residual soil (R); saprolite (S).

Fig. 7. Residual layer (sample SD-01/2.0 m) can be classified as clayey sand, with percentages of sand and silt of 53 and 25 %. The soil samples representative of the saprolite layer showed a significant variation in 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 is in agreement with the textural characteristics of its parent material (migmatitic gneiss). Therefore, it is expected

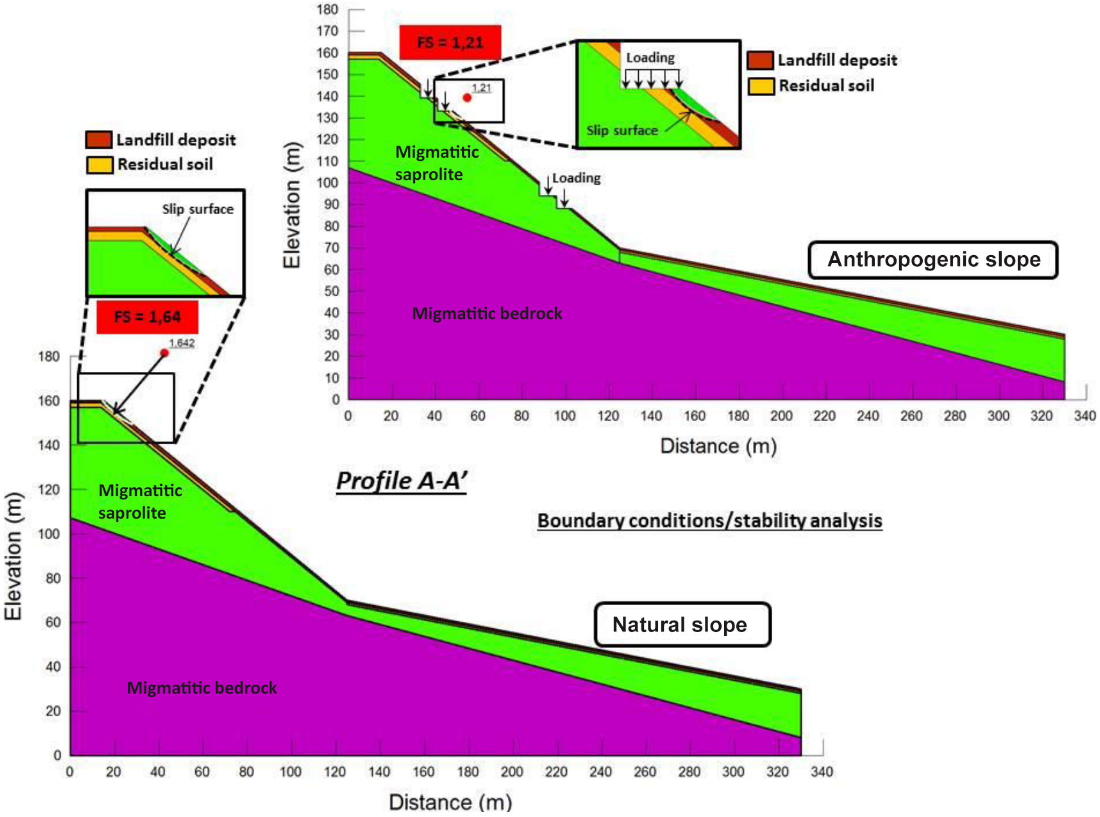


Figure 6. Slope geometry and boundary conditions used in the stability analysis with natural and anthropogenic factors (rainfall, cut slope, loading and leakage).

that the mechanical and hydraulic properties of this soil layer present high variability. 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 strength parameters (c’ and φ') and saturated hydraulic conductivity (Table 2), the values representative of the saprolite 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 high values of the resistance parameters shown in Table 2 can be explained with the high heterogeneity of the residual gneiss soil, such as the presence of quartz particles and other minerals of considerable size in the specimens tested, which confer them high resistance. In addition, the values of the resistance and Ksat parameters obtained in this study are close to mean reference values of residual gneiss soils that are representative of other Brazilian sites (Costa Filho and Campos, 1991; Ahrendt, 2005; Reis et al., 2011).

Figure 8 shows the water retention curves of the soil layers that are representative of the profiles. In general, the residual and saprolite layers are able to hold more water than 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 saprolite layers are 0,06, 0,24, 0,26 $\mathrm{m}^3\,\mathrm{m}^{-3}$.

3.2 Soil moisture data

Soil moisture data from 2016 from the EnviroScanTM probes (3G1 and 3G2) are presented in Fig. 9. The data from 3G1 (upper graph of Fig. 9) showed that in the sensor installed at a lower depth (0.5 to 1 m), which is representative of the landfill deposit (green curve) layer, variations are larger than moisture variations ($\Delta\theta = 32\,\%$), with maximum and minimum water content values recorded in March (46 %) and April (14 %), respectively. At deeper layers (1–3 m deep) that are representative of the residual and saprolite layers (black and red curves), time variation of soil moisture is much lower ($\Delta\theta = 10\,\%$, on average). In the 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 saprolite layer (red curve), the maximum soil moisture value occurred in June (40 %) and and the minimum in May (32 %). The different dynamics among the three soil layers not only reflect differences in the retention properties of each layer considered but also the deep soil

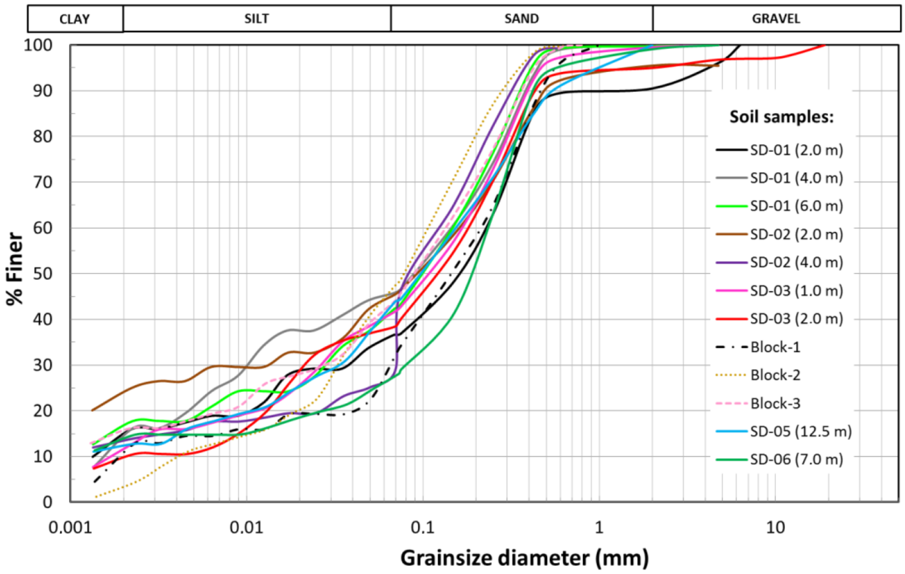
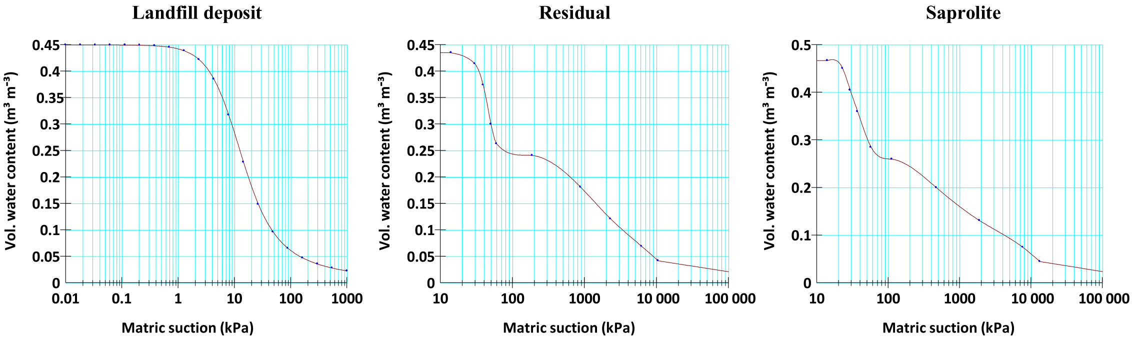


Figure 7. Granulometric distribution for the residual soil and the saprolite of the six boreholes analysed (SD-01 to SD-06) and for the undisturbed soil cores (Block 1 to Block 3).


Landfill deposit

Residual

Saprolite

Figure 8. Water retention curves of the three soil types used in transient seepage analysis.

water dynamics down through the soil profiles. This explains why the upper layer (landfill deposit) shows a more spiky behaviour in response to the rainfall, while the other two layers exhibit gradual and delayed variations related to deep water percolation.

Analysing the data on the probe 3G2 (lower graph of Fig. 9), 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. Deeper within the residual and saprolite layers (black and red curves), time variation of soil moisture variation is similar to 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 saprolite layer (red curve) the maximum was observed in January (37 %) and the minimum occurred in August (30 %).

Contrasting differences in the soil moisture behaviour of the landfill deposit from the probes 3G1 and 3G2 suggest that the variability of soil parameters is higher in the 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 GEO-SLOPE simulations input data

Table 3 summarizes the parameters used in the numerical simulation with GEO-SLOPE 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

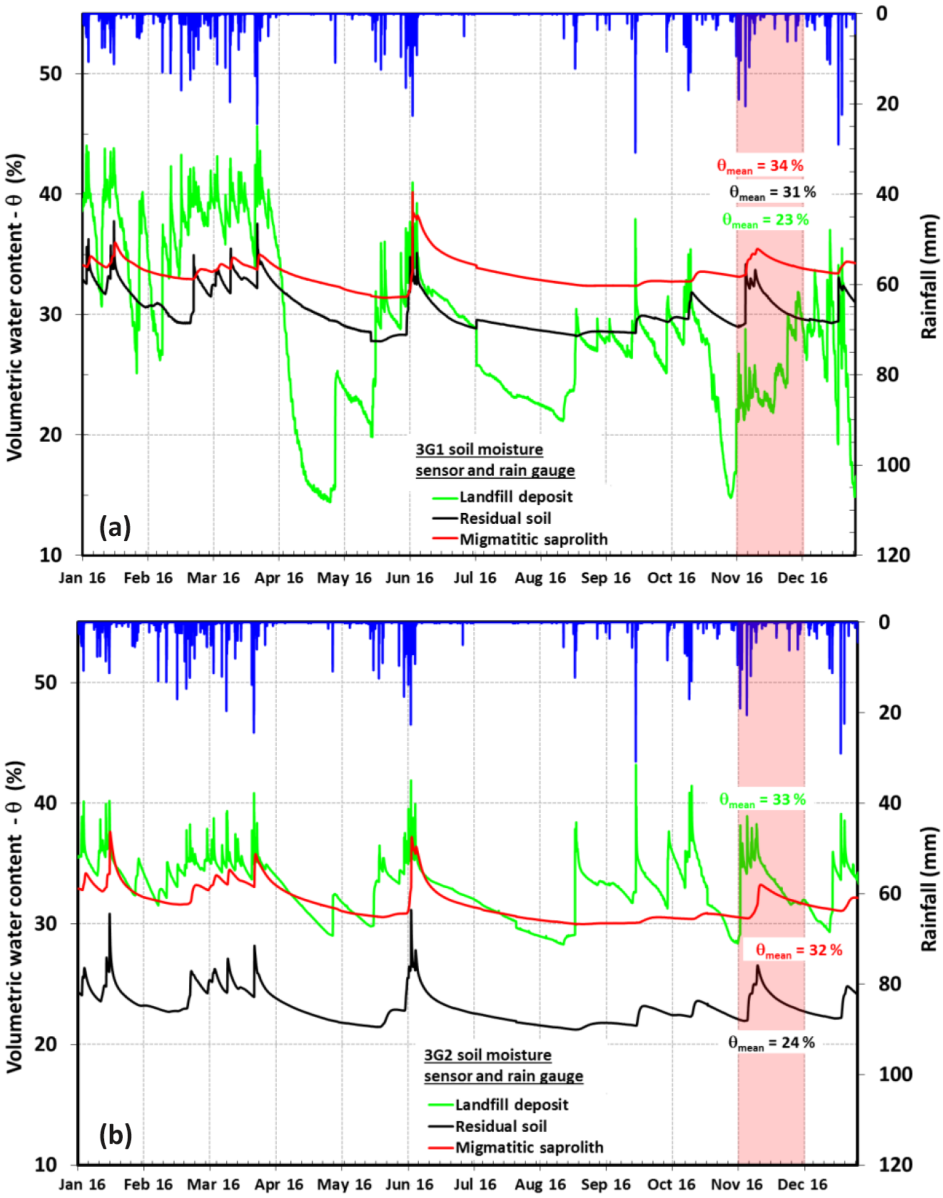


Figure 9. Time variation of soil moisture at different depths during 2016 in the study area measured with the sensors 3G1 **(a)** and 3G2 **(b)**.

density and saturated hydraulic conductivity parameters for saprolite 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 $\mathrm{m^3\,day^{-1}}$ (SABESP, 1993, 2016) for simulations that include leakage, distributed load due to single-storey housing of 2.0 $\mathrm{kNm^{-2}}$ (ABNT, 1980) and height of the cutting slope (based on field data). In the case of the simulations that include leakage, one constant value of 1.0 $\mathrm{m^3\,day^{-1}}$ was considered in the cut slope, from the 10th day of the simulation to 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 helped 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 initial conditions of the simulations were derived assuming initial soil moisture values of 0.33, 0.31 and 0.34, for the landfill deposit, residual and saprolite layers. These values correspond to the average of the highest soil moisture values of the two probes dur-

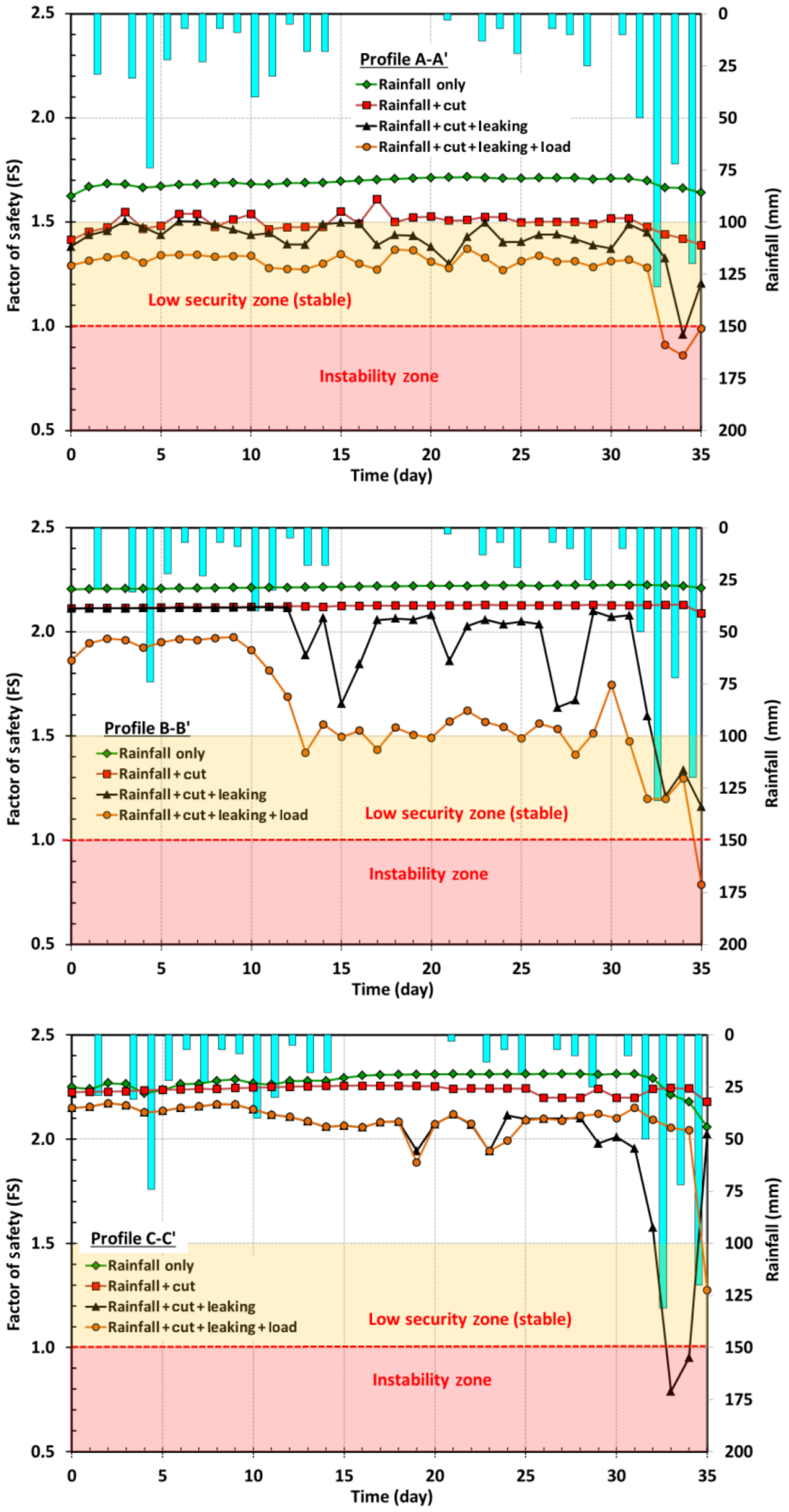


Figure 10. Time variation of the slope safety factor for natural conditions and taking into account the additional effects introduced by anthropic disturbances on profiles A–A′, B–B′ and C–C′.

ing November 2016 and are indicated by the light-red-shaded area of Fig. 9.

Subsequently, the mean moisture values were used to obtain the initial values of matrix suction from the representative water retention curves in each layer of the profile (Fig. 8). 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 1 December 1999 to 4 January 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 saprolite.

3.4 Slope safety factor analysis

Figure 10 shows the time variation of the slope safety factor (FS) during 35 days for the 2000 rainfall for the three profiles. In Fig. 10, two “warning zones” are considered: zone of instability $\mathrm{FS} < 1.0$, where ruptures should occur and low stability zone, $1.0 < \mathrm{FS} < 1.5$, 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 ($1.3 \leq \mathrm{FS} < 1.5$), mean ($1.15 \leq \mathrm{FS} < 1.3$), low ($1.0 \leq \mathrm{FS} < 1.15$).

For all three profiles analysed, it is clear that the effect of daily rain on the decrease in the FS (green line) was practically insignificant, with FS values above the 1.5 threshold (high safety degree of the slope), indicating a very low likelihood of landslides. In the rainfall-only scenario, the variations in FS values are due to the geotechnical and 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 (Fig. 4) and the water table profile, which is 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 Fig. 10), it was verified that terrain cuts had a minor effect on the slope safety factor. Except for the case of the A–A′ profile, which presents the FS condition < 1.5 between the 32th and 35th days 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 in FS was more pronounced than in the other profiles analysed, which was directly related to the positioning of the cuts considered along the slopes and located based on field information. The configuration of the cuts used in this profile favour the wetting of the topsoil and consequently affected the whole profile stability.

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^3)*	Rainfall (m day^{-1})	Ksat (m s^{-1})	Pore water pressure (kPa)	Level of the water table	Load in the slope (kN m^{-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 $\varphi' = 31°$	14,9	Rainfall events of the 2000 year	9.50×10^{-6}	−7	Data on SPT	2.0	6.0	1.0
B–B′	16–33	95	residual	$c' = 15$ kPa $\varphi' = 36°$	18,3		4.44×10^{-6}	−40				
C–C′	15–35	87	saprolite	$c' = 21$ kPa $\varphi' = 43°$	19,1		5.43×10^{-6}	−40				

* Fill deposit (geotechnical parameters from Ahrendt, 2005).

The third scenario of Fig. 10 (black line), which considered the joint influence of two anthropic factors (cut and leakage) and the rainfall of 2000, shows significant variations in the FS values. 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 32nd and 35th days of simulations in the case of the B–B′ profile and on day 17 for the C–C′ profile. It should be noted that, after the 11th after the beginning of simulation, FS values become sensitive to rainfall variability.

In addition, it can be seen in Fig. 10 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 in 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 32nd and 35th after the beginning of simulations, in response to the significant rainfall that occurred in this period. However, it is observed that, under the influence of leakage, rainfall history played a role, since the factor of stability is previously before the large rainfall event at the end of the simulation period. This can be seen more clearly in the profile B–B′ of Fig. 10: in the dry period between day 15 and day 22 after the beginning of simulation, a quick recovery of the stability of the simulations is verified, which includes the effect of leakage (black curve), which is interrupted with the return of the rainfall.

Finally, in the fourth scenario of Fig. 10 (light-brown line), all the anthropic factors (cut, leakage and housing load) are considered together with the daily rainfall. Most of the time, FS values remained below the threshold of 1.5 in the A–A′ and B–B′ profiles, but only after the day 34th of the simulation in the case of the profile C–C′. 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 failure surface estimated by the numerical model was different from that assumed in scenario 3 (black line).

Based on the assessment of the slope safety factor presented in Fig. 10, it is clear that the probability of landslides associated with the 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 decrease in the safety factor in all profiles studied, although the effect varied between slopes depending on the geological–geotechnical profile characteristics, geomorphological conditions, water table position and the anthropic conditions, that is, the positioning of cuts, leakage and housing load along the slope.

In general, slopes became unstable ($FS < 1.0$) between the 32nd and 35th days after the beginning of simulations when high daily accumulated values were verified. Since most of the landslide occurred on day 32, it follows that the model successfully predicted the time at which the landslides began. However, it should be noted that previous accumulated rainfall values were crucial to creating favourable conditions for triggering landslides as shown by Fig. 10 after the 30th day from the beginning of the simulation.

Santoro et al. (2010) recommended in situ technical surveys of urban hazardous areas after accumulated 72 h rainfall equal to 60, 80 and 100 mm (depending on the municipality) in order to identify evidence of the imminence of landslides and to enforce eventual preventive removal of the population. It can be seen in Fig. 10 that the 72 h of accumulated rainfall was 35 mm for day 30 after the beginning of simulation, 35 mm for day 31, 60 mm for day 32 and 191 mm for day 33. Thus, critical rainfall thresholds (60–100 mm) were exceeded between the 32nd and 33th days for the events recorded in the year 2000.

In this period, the FS in the three analysed profiles presented the lowest values, located exactly between the low-medium security zone ($1.0 < FS < 1.3$) and the 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 the landslides. Although the 72 h 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 prior to the landslides was crucial to bringing FS values closer to critical levels, indicating that the critical value presents limitations on slopes that were initially drier.

4 Conclusions

The GEO-SLOPE model proved to be an efficient and useful tool with which to predict the landslide in the 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 were accurate for the prediction of occurrences of landslides on urban slopes.

Regarding the use of critical values of rainfall in early warning systems by CEMADEN and the civil defence for the Campos do Jordão municipality, although adequate for the event of 2000, our study shows that the previous rainfall history, in combination with leakages, played a fundamental role in creating favourable conditions for the occurrence of landslides. This is related to the fact that leakages contribute to keeping the soil profile closer to saturation at the beginning of the period of more intense rainfall, and consequently the developing of positive pore-pressure conditions. In other words, the threshold currently used for issuing early warnings would result in late alarms, at least in heavily disturbed landscapes.

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 in 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, that is, due to the presence of several cuts along the slope combined with construction and leakage. Clearly, human interventions on natural slopes play a fundamental role in triggering landslides in heavily populated steep slopes surrounding urban areas. Since shallow landslides in the study area usually occur in cut-and-fill slopes, the rupture surface size and the amount of material mobilized do not vary significantly among the events. Therefore, the most useful information for an early warning system perspective is to know whether the value of FS is below 1.0, regardless of how far below that threshold the slope safety factor is. Other relevant information is the timing of the landslide events, which is crucial to determining the rainfall thresholds for issuing an early warning. Therefore, information about the rupture surface size, which is essential for assessing potential damages, is beyond the scope of this study.

Considering that the pattern of land use and construction used in the simulations is representative of most neighbourhoods of Brazilian urban areas, the methodology used in this paper needs to be repeated and verified in other areas in order to establish more accurate critical threshold that trigger landslides. Moreover, since the landslide-prone areas of Campos do Jordão municipality are not the most populated of Brazil, for instance, compared 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 that using the slope safety factor is viable for determining a more accurate rainfall threshold that triggers landslides, with direct impacts on the credibility of early warning systems, which relies on 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. Since simulation results indicated that the slope safety factor FS was sensitive to both geotechnical and anthropic factors, future studies of slope stability probabilistic analysis are needed, which takes into account the wider range of parameters values that occur in the study area.

Finally, considering that this work has 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 that identify landslide-prone areas are essential, since many urban areas of Brazil lack zoning of hazardous areas, which is essential for implementing regulations. Besides this, educational campaigns regarding the adoption of better construction practices and reduction of piping leakage will be helpful in already consolidated occupied areas.

Data availability. The precipitation data can be accessed through the website: http://www.cemaden.gov.br/mapainterativo/ Geotechnical data and numerical experimental results can be directly requested from the authors.

Competing interests. The authors declare that they have no conflict of interest.

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