This is a pre-print of an article published in Geotechnical and Geological Engineering. The final authenticated version is available online at: https://doi.org/10.1007/s10706-019-01054-1.

Geohazard assessment of landslides in south Brazil - Case Study

Authors:

Omar Hamza (corresponding author, o.hamza@derby.ac.uk)

The University of Derby, College of Engineering and Technology, Markeaton Street, Derby DE22 3AW

Tiago De Vargas

1) Municipal Water and Sewage Service (SAMAE), Department of Water Resources, Address: Pinheiro Machado, 1615, Caxias do Sul, Brazil. Postal Code: 95020-170.

2) Centro Universitário da Serra Gaúcha (FSG), Department of Civil Engineering, Address: Os Dezoito do Forte, 2366, Caxias do Sul, Brazil. Postal Code: 95020-472.

Fernando Eduardo Boff

Centro Universitário da Serra Gaúcha (FSG), Department of Civil Engineering, Address: Os Dezoito do Forte, 2366, Caxias do Sul, Brazil. Postal Code: 95020-472.

Yawar Hussain

Department of Civil and Environmental Engineering, University of Brasilia, ICC Norte, 0910-900 Brasilia-DF, Brazil.

K. Sian Davies-Vollum

Environmental Sustainability Research Centre, College of Life and Natural Science, University of Derby, Derby DE22 1GB

Abstract:

Slope instability phenomena such as mudslides represent a major geohazard in Brazil, which has caused devastation in many states and affected the lives of people, particularly in self-built settlements on steep slopes. This paper presents and discusses slope stability issues encountered in Caxias do Sul in the State of Rio Grande do Sul, which exemplifies the existing situation of landslide risk assessment in southern Brazil. Local geology and ground conditions of the area in relation to slope instability were reviewed and gaps in information required for mitigating risk were identified, such as inadequate geotechnical information and lack of full inspection and continuous monitoring of active landslides. Although risk assessment has been developed for the city and regarded as a fundamental management tool in the mitigation of landslide hazards, the study showed that the risk assessment works are outdated and not effectively considered for the development of the city. With significant unplanned urban expansion (where houses have been self-built on very steep terrains without geotechnical assessment of the ground and slope conditions), new geohazard mapping is essentially required. Several key recommendations were provided for mitigating the destructive effect of landslides and improving their management in mountainous urban settings.

Keywords:

Landslide, Geohazard assessment, Slope stability, Caxias do Sul, Risk assessment

1. Introduction

Geohazard is a general term commonly used to describe a wide range of environmental and geological processes that impact human activities. Landslide (or downslope movement) is one of the major geohazards widespread in Brazil. The lack of adequate urban planning combined with factors related to climate, geology, geomorphology and vegetation cover has demonstrated the vulnerability of society to such natural disasters, which inevitably cause human and economic losses (Souza and Sobreira, 2014). Various scales of landslides are prevalent across Brazil and the country is expected to have one of the highest annual mortality risk levels of landslides in the world (Shi et al., 2015). For example, in January 2012, circa 26 centimetres of rain, fell in the Serra do Mar mountain region and nearby cities of Teresópolis and Nova Friburgo (Southeast Brazil). The downpours triggered flash floods and mudflows, causing more than 800 casualties and leaving at least 8,700 homeless (Agencia Brazil, 2012).

A large percentage of the Brazilian population occupies unplanned urban areas (De Espindola et al., 2017) that are susceptible to different geohazards. These areas are generally located on steep slopes and river floodplains, without adequate infrastructure such as sewage systems. This unplanned urban growth has been going on for a long time, most notably in the 1980's - 1990's (De Espindola et al., 2017). In response to this challenge, the Brazilian government has created a Federal Law (Federal Law 12,608 - April 2012) that enforces and regulates landslide risk assessment, particularly for areas with existing settlements or with potential urban expansion. This important step has pushed local authorities as well as federal research institutes and universities to actively participate in the development of geohazard mapping (zoning). However, this development has been challenged by several obstacles where urban expansion does not make use of the risk assessment works.

In this paper, the city of Caxias do Sul has been selected as a case study for an urban area experiencing typical slope stability problems in southern Brazil. Factors influencing slope stability conditions in the city, such as climate, precipitation, geomorphology, and geology are discussed. The study presents the landslide risk assessment carried out for the city and highlights the shortcoming of the existing information required for mitigating landslides' risk.

This is a pre-print of an article published in Geotechnical and Geological Engineering. The final authenticated version is available online at: https://doi.org/10.1007/s10706-019-01054-1.

Key recommendations are made to support federal institutions and local authorities in improving their existing approach to managing risk related to slope instabilities.

2. Location and geomorphology of Caxias do Sul

Caxias do Sul city is located in the State of Rio Grande do Sul, southern Brazil (between the coordinates of longitude 51°18'00"W - 50°42'00"W and latitude 29°20'00"S - 28°48'00"S) as shown in **Figure 1**. According to the Brazilian Geography Institute (2010), the total population counts 435,482 inhabitants (419,321 and 16,161 occupy urban and rural areas, respectively) and has a regional area of 1,643.913 km^2.

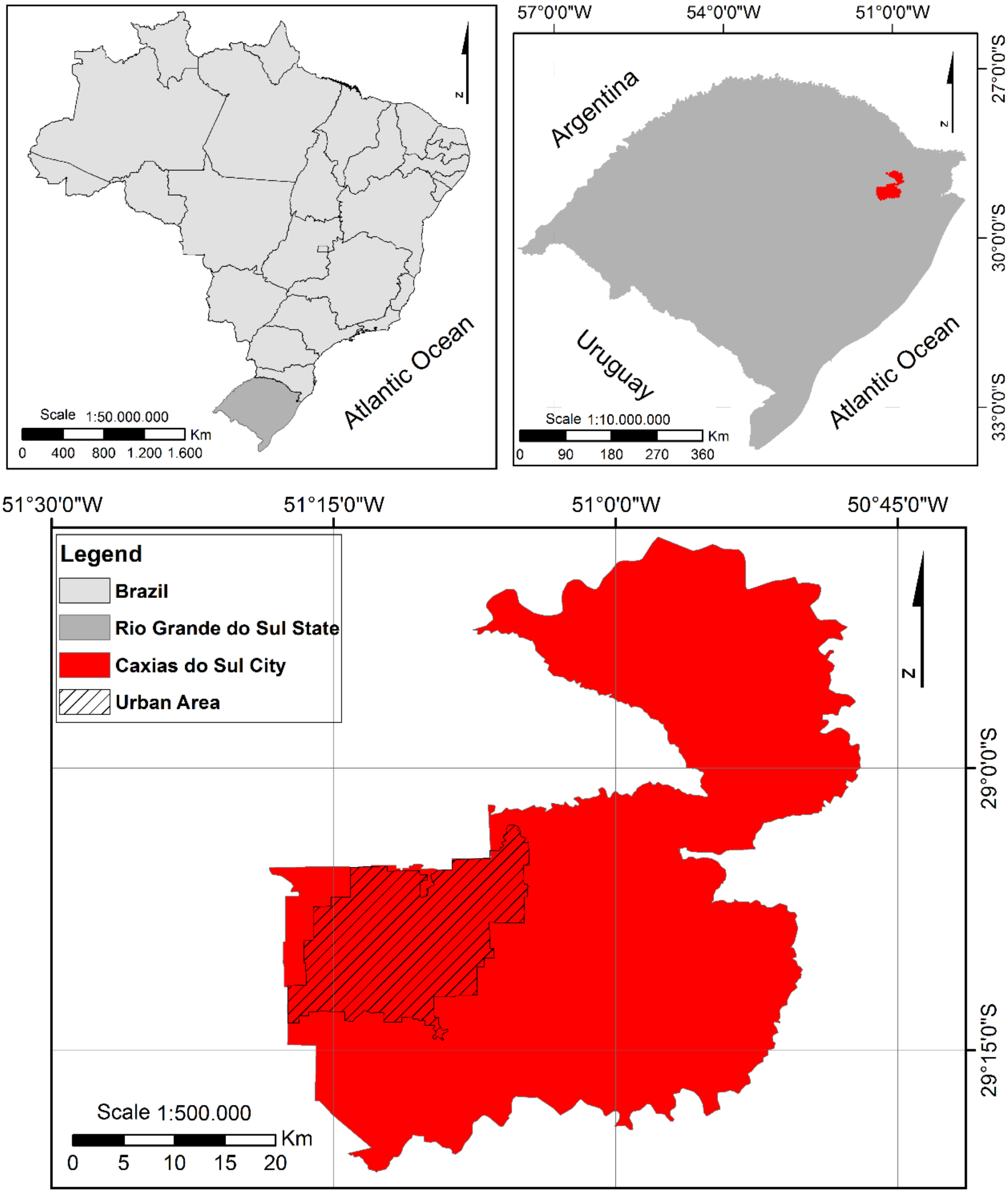

Fig 1. Location of the city of Caxias do Sul.

This is a pre-print of an article published in Geotechnical and Geological Engineering. The final authenticated version is available online at: https://doi.org/10.1007/s10706-019-01054-1.

Two geomorphological units can be observed in the Caxias do Sul: Plateau of Campos Gerais and Serra Geral. The Plateau of Campos Gerais unit is predominant in the municipality and presents a relief dip in the S - SW direction, with maximum height of 942 meters. In the region of higher elevation, the relief is flattened not dissected, with flat bottom valleys and many springs and wetlands associated with structural lineaments. There is a thick mantle interspersed with stony areas and few thick soils (Lisboa et al., 2003). The Serra Geral geomorphological unit is observed in the valleys of the Caí and Antas rivers and has cliffs with East-West direction. At high altitude, there are abrupt sub-vertical rocky slopes in acidic volcanic rocks (details of geology are discussed in Section 5), where frequent falls of blocks occur. The middle part is composed of basalts with significant deposits of talus and colluvium and experiences several types of mass movements (see Section 7), which cover the Botucatu Formation sandstones (Lisboa et al., 2003).

3. Landslides' record in Caxias do Sul

Before presenting the contextual information (climate, geology, ground condition, and type of mass movements) it is necessary to understand the frequency of landslides recorded in the city. According to Argenta et al. (2009), based on available data from the local authority, there were 31 landslides in the municipality of Caxias do Sul between 1980 and 2007. The greatest number of events occurred in 1993 and 2007 (as shown in **Figure 2**) and that the largest concentration of landslides took place in the months of June, July and August, coincident with the highest period of precipitation in the municipality. The recorded average monthly rainfall is shown in **Figure 3**. Additional 49 landsides have been reported by Wiggers (2014) which indicates the significance of the problem in the city of Caxias do Sul.

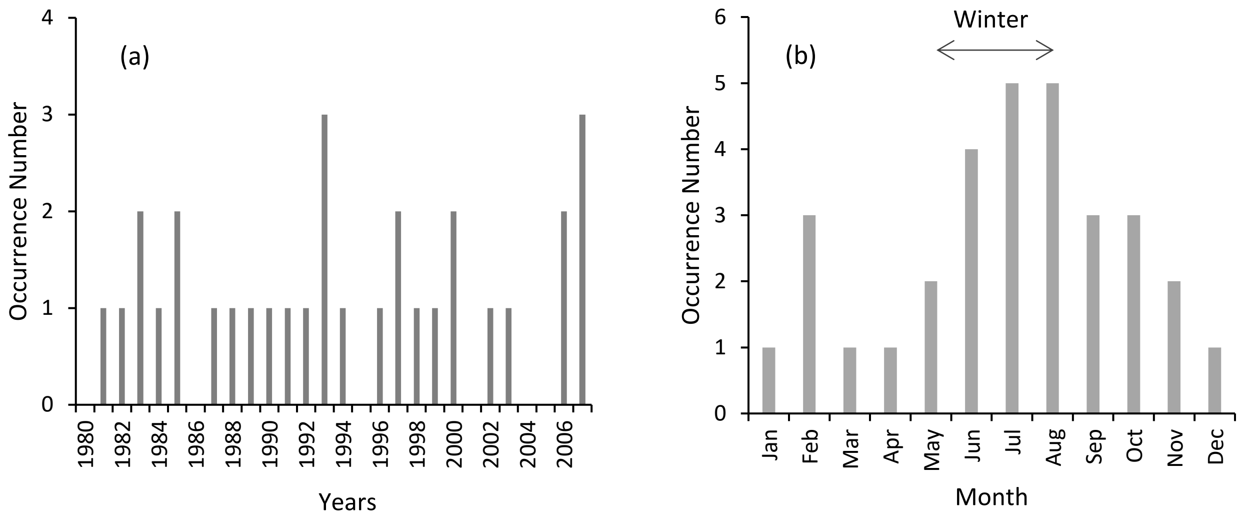

Fig 2. Graphical representation of (a) the annual and (b) monthly distribution of the occurrence of landslides in the city of Caxias do Sul, from 1980 to 2007 (Source of data: Argenta, 2009).

4. Climate and Hydrographic conditions

Rainfall and temperature play important role in soil erosion and rock weathering affecting the stability of slopes, therefore it is useful to understand the climate and hydrographic conditions of the region. According to Köppen climate classification system, Rio Grande do Sul State is located in *temperate* climate zone "C", specifically zone "Cf" or *humid temperate* (Camargo, 1991). Within this state, the region of Caxias do Sul is defined as “Cfb” (warm temperate). The annual average temperature is 17.2° C, while the annual average of the maximum and minimum temperatures are 28.9° C and 12.9° C, respectively. However, the occurrence of severe frost is frequent, with 10 to 25 days annually. The average annual relative humidity is 76%, while the registered sunshine is about 2,240 hours of the annual total of solar brightness. The average rainfall accumulated is 1,915mm. As presented in **Figure 3**, the historical precipitation of the municipality of Caxias do Sul shows two periods of higher rainfall, between August and October, reaching a value slightly greater than 170 mm and in the month of January that presents a quantity of 150 mm.

This is a pre-print of an article published in Geotechnical and Geological Engineering. The final authenticated version is available online at: https://doi.org/10.1007/s10706-019-01054-1.

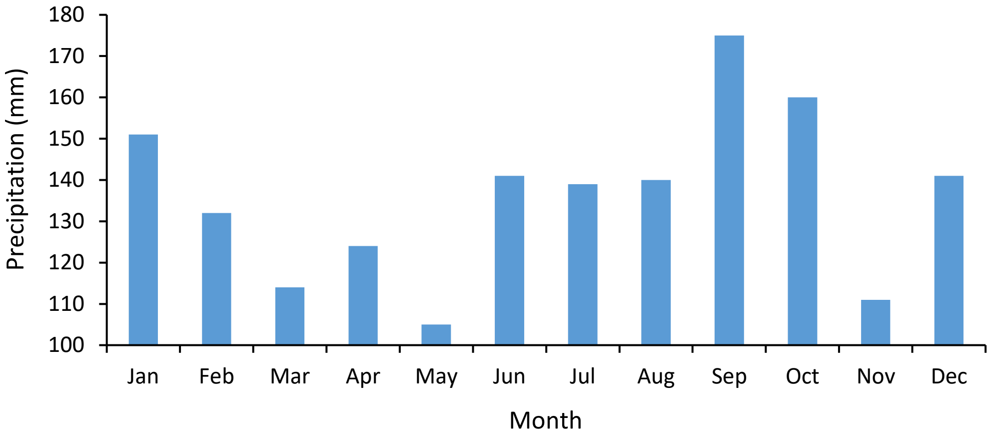

Fig 3. Average monthly rainfall from 1948 to 2004, excluding the duration from 1979 to 1985. (Source of data: Caxias do Sul Municipal Airport and Fepagro).

5. Geology of the area

The Caxias do Sul region is located within the intracratonic basin of the Paraná Province, which contains the São Bento Group, consisting of the sedimentary units of Guará and Botucatu Formations, and the volcanic package of the Serra Geral Formation. The volcanic package is tholeiitic, represented by basalts to andesitic-basalts in the bottom sequence, and an acidic (felsic) sequence of rhyolites to rhyodacites in the upper portion. The felsic sequence comprises two types of ignimnbrites Palmas (aphyric to lightly microporphyritic) and Chapecó (porphyritic), forming tabular layers (Roisenberg and Viero, 2000). The region of Caxias do Sul is mainly covered by units of the Palmas type (total thickness of 300 m) while basalts and andesitic-basalts occur in the lower levels, along the valleys, rarely interbedded with acidic ignimbrites. The geological map of the city is shown in **Figure 4**.

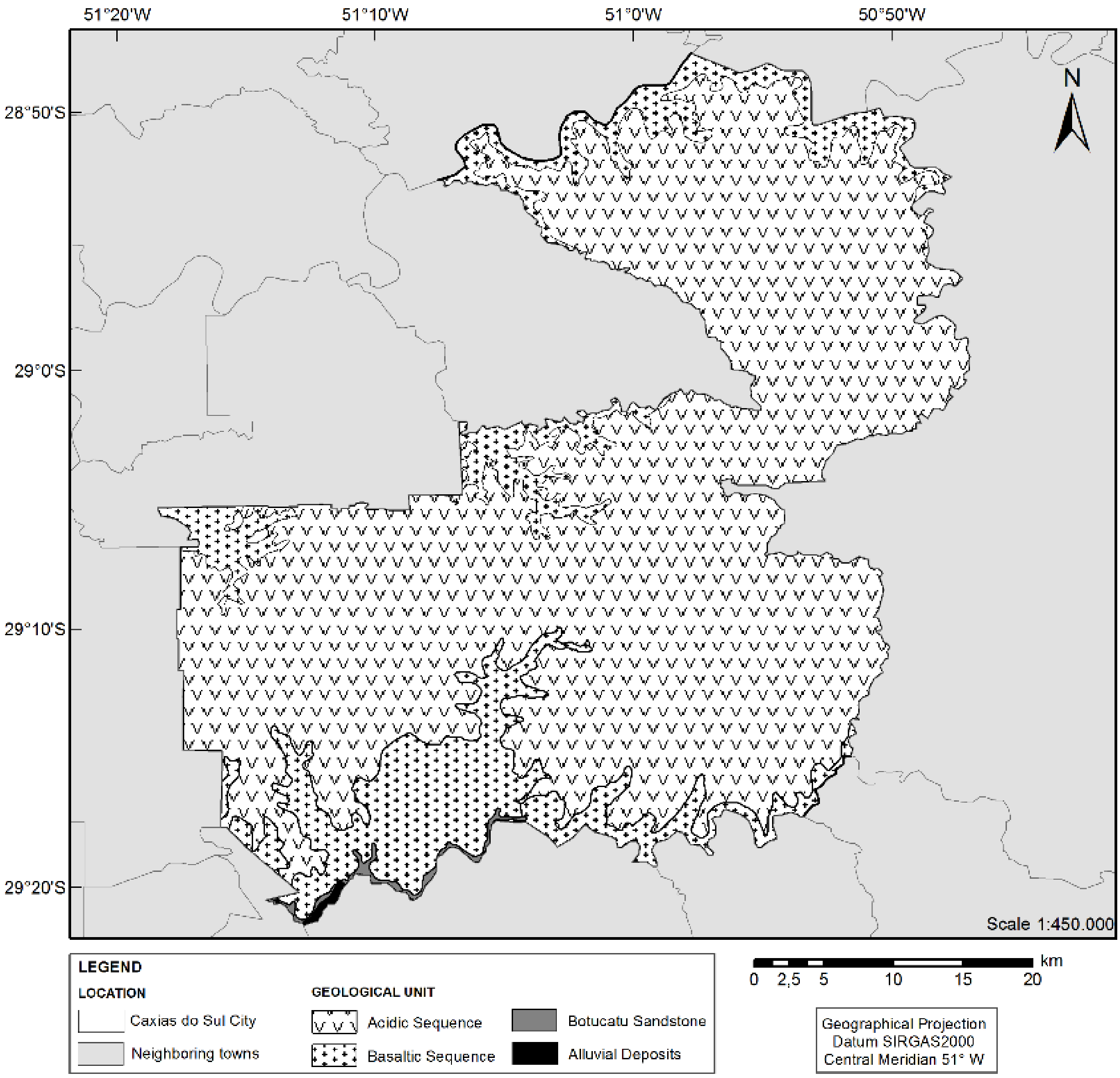

Fig 4. Geological map of Caxias do Sul city (After CPRM, 2010).

A geological-geotechnical study (Bressani *et al.*, 2005) carried out within the urban area of Caxias do Sul classified the rock type Palmas (Facies Caxias) as Dacite rocks. From the bottom of the volcanic sequence the following units were defined: Dacite Galópolis, Dacite Canyon, Dacite Carijó and Dacite Ana Rech. **Table 1** presents a stratigraphic column of the lithologies of the Municipality of Caxias do Sul where the thickness of each volcanic unit and the respective soils derived from the alteration of these rocks is indicated.

This is a pre-print of an article published in Geotechnical and Geological Engineering. The final authenticated version is available online at: https://doi.org/10.1007/s10706-019-01054-1.

Table 1. Geology of the Municipality of Caxias do Sul (Extracted from Bressani *et al.*, 2005)

Period	**Age (Ma)**	**Lithostratigraphic Unit**	**Rocks**		**Thickness (m)**	**Soils**
Lower Cretaceous	128	Serra Geral Formation	Caxias	Dacite Ana Rech	80	Ana Rech
				Dacite Caxias / Carijó	170	Forqueta Caxias/Carijó
				Dacite Canyon	70	Canyon
				Dacite Galópolis	70	Galópolis
			Basalts and Andesi-basalts Gramado		450	-
Jurassic	138	Botucatu Formation	Aeolian Sandstones		160	-

Observing the stratigraphic correlation, in urban areas, Bressani *et al*. (2005) found that the Dacite Ana Rech shows marked horizontal stratification throughout its area of occurrence (reaching a thickness of about 900 meters), while the Dacite Carijó/ Caxias shows colouration predominantly from light olive to grey and massive flow banding as shown in **Figure 5**. According to Roisenberg & Viero (2000), the lower and upper portion of this lithological unit has intense horizontal tabular demarcation, which is subnormal to magmatic flow structures. These structures are occasionally filled by fine quartz, albite and zeolite venules, while the central portion is massive or vertical fracturing. In the urban area of Caxias do Sul, Bressani *et al*. (2005) described the massive zone as 30 meters thick, and the tabular strata sub-horizontal in the basal portion as 5 to 30 centimetres thick.

The stratigraphic unit defined as Dacite Canyon usually occurs between heights of 680 and 750 meters. They are acid rocks characterised by vertical flow structures with dark grey to reddish brown colour (**Figure 6**), apphyric texture, plagioclase and pyroxene micro-phenocrysts, opaque and residual quartz, a matrix of microlites of the same minerals, as well as partially recrystallized glass (Lisboa *et al*., 2003; Bressani *et al*., 2005). Locally it fractures parallel to the lamination, with fractures filled by fibrous chalcedony and carbonates.

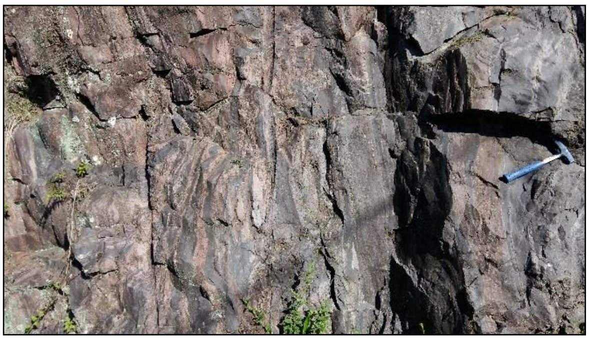

Fig 5. Dacito Caxias unchanged. **Fig 6.** Vertical fault observed in Dacite Cânyon.

6. Geotechnical conditions of slope materials

The Dacite Ana Rech forms course-grained soils, with incipient horizons of saprolithic soils. This soil is found in plateau regions at heights between 780m and about 900m. This altitude favours drainage and oxidation, forming brown-yellowish soils that are non-plastic, with considerable shear strength (Bressani *et al*., 2005). Generally, it does not present geotechnical problems, except in the interface with Forqueta soil, which is positioned immediately below Ana Rech soil. In these cases, the topography becomes very steep and can generate risk situations due to the relatively low resistance of the interface and the lower material.

The Dacite Caxias / Carijó in its top portion includes distinctive flow structures similar to those presented by Dacite Canyon. These structures increase the interaction of water with rock, so it accelerates the process of chemical weathering, leading to the formation of a plastic soil. In areas where this material is at higher elevations with good drainage, thick soils with more mature pedological characteristics are developed. These can evolve to soils of medium plasticity, red with bands of alteration and originate mainly from the upper glassy portion of the Dacite Caxias / Carijó which are called Forqueta, shown in **Figure 7-a** (Bressani *et al*., 2005).

The middle portion of the Dacite Caxias / Carijó rock formed thick saprolite soil with silt-sandy characteristics and they are considered non-plastic. Its granulometry (grain size distribution) is dependent on the degree of weathering, particularly as it has fragile grain aggregates. The Caxias / Carijó soil (**Figure 7-b**) is characterised as a low-plasticity to non-plastic saprolite, grey to slightly reddish colour, with generally well-visible horizontal layered structures, originating from the alteration of the median portion of the Dacite Caxias / Carijó (Bressani *et al*., 2005).

The Canyon soil is characterised as plastic to very plastic, red to reddish-brown colour, occurring in an extensive area of the region of Caxias do Sul (**Figure 7-c**). This soil can be of significant thickness and is clay rich, which is associated with unstable volumetric behaviour and geotechnical problems. This soil may contain expansive clays originating from the decomposition of the thick upper portion glassy of the Dacito Canyon.

Galópolis soils (**Figure 7-d**) are generally found in slope deposits (or colluvium) formed by residual soil moved from the upper layers. The dacites present in the lower valleys

This is a pre-print of an article published in Geotechnical and Geological Engineering. The final authenticated version is available online at: https://doi.org/10.1007/s10706-019-01054-1.

(470m to 600m) show a marked degree of weathering due to their mineralogy as well as the high humidity in these regions. These are plastic soils originating from the Dacite Galopolis and generally observed in mixture with materials transported from other places.

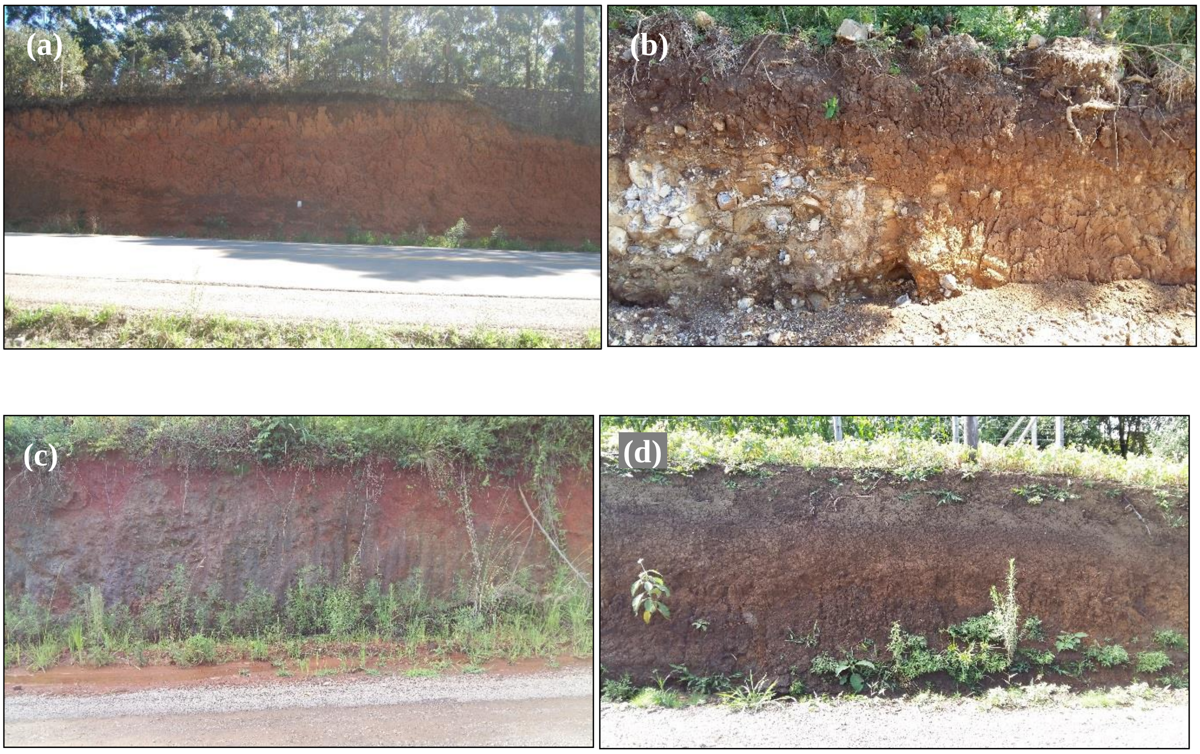

Fig 7. Common types of soils in Caxias do Sul: (a) Forqueta, (b) Caxias, (c) Canyon, and (d) Galopolis.

The saprolite soils (represented by Forqueta, Canyon and Galópolis) found in the urban area of the city of Caxias do Sul, contain both plastic and non-plastic materials. Silt and clay represent 70 to 80% of grain sizes distribution and the Plasticity Index (PI) varies between 18 and 22.5%, while Liquid Limit (LL) is between 58 and 71.5% (**Table 2**). According to Bressani *et al.* (2005), sample PTC-050 (in **Table 2**) presents a typical transitional behaviour between a pedologically evolved plastic soil and the original rock (saprolite). The soil is classified as high to very high plasticity Silt (according to BS 5930 in Craig, 2004) as presented in **Table 2** and **Figure 8**.

Table 2. Results of geotechnical testing conducted on the saprolite soils (After Bressani *et al*., 2005).

Sample	Grain size distribution (%)			Plasticity indices			Classification
	Clay	Silt	Sand	LL	PL	PI	
PTC-031	38	42	20	71	48.5	22.5	MV - SILT
PTC-033	36	29	35	58	37	21	MH - SILT

PTC-051	29	31	40	71	52.5	18.5	MV - SILT
PTC-062	-	-	-	66	48	18	MH - SILT
PTC-107	-	-	-	68	45.5	22.5	MH - SILT
PTC-050	24	46	30	Not Plastic			-

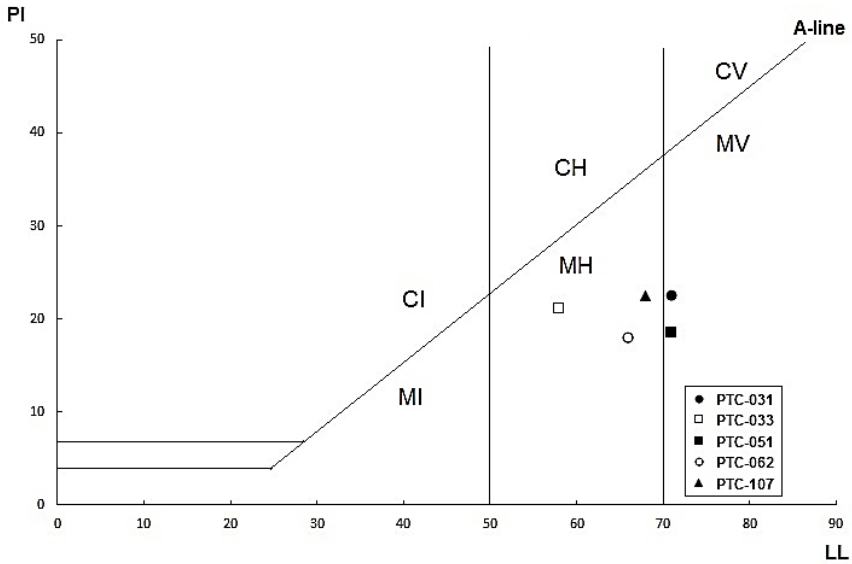

Fig 8. Plasticity Chart for the saprolitic soils. LL= Liquid Limit; PI=Plastic Limit; C=Clay; M=Silt; I, H, V = Intermediate, High, Very high plasticity.

Another study carried out by Rigo (2005) on the Serra Geral geological formation in the State of Rio Grande do Sul (Southern Brazil) evaluated the properties and geotechnical behaviour of the saprolite soils formed from the basic and acidic volcanic rocks. The samples were collected from Caxias do Sul, in the Kaiser neighbourhood. This area had downslope movement due to discontinuities with unfavourable inclinations, which are filled by red clay that controls the mechanical behaviour of the discontinuities. Rigo (2005) studied the geotechnical characterisation of the saprolite soil (Sample: Kaiser SS) and the red clay (Sample: Kaiser AV) observed in the Kaiser neighbourhood. The soil samples were generally described as a clayey matrix with some minerals. Several tests were conducted on both soils to determine their engineering properties. The values of the specific grain weight observed in the samples Kaiser-SS and Kaiser-AV were 26.68 and 26.16 (γ_s – kN/m^3), respectively. The other physical testing were performed only for the Kaiser-SS sample and presented apparent wet specific weight (average) 16.42 (γ_t – kN/m^3) and average porosity 52.38 (n - %). According to Rigo (2005), the Kaiser-SS sample had no plasticity, and it was classified as ML - Sandy silt.

However, the Kaiser-AV sample showed Plasticity Index (PI) values of 42, Liquidity Limit (LL) of 87 and Plasticity Limit (PL) of 4, classified as MH – High plasticity silt with sand. Shear strength parameters (effective friction angle, ϕ' and cohesion, c') were obtained by Triaxial and Ring Shear test; the results are presented in **Table 3**.

Table 3. Shear Strength Parameters of saprolite soils (source: Rigo, 2005).

Sample / Method	Basis of interpretation	ϕ' (°)	c' (kPa)
Kaiser-SS / Tiaxial	Peak	34.9	52.3
	Residual	29.3	32.7
	Through origin (no cohesion)	24.2	-
Kaiser-AV / Triaxial	Best fit to experimental points	17.5	6.7
	Through origin (no cohesion)	18.4	-
Kaiser-SS / Ring Shear	Best fit to experimental points	26.4	6.5
	Through origin (no cohesion)	27.2	-
Kaiser-AV / Ring Shear	Best fit to experimental points	17.4	9
	Through origin (no cohesion)	18.5	-

These engineering properties of the two soils can be discussed in the cotext of slope instability. Although the main soil (Kaiser-SS) comprising the slope is non-plastic and has relatively large shear strength, the existence of high plastic weak soil (Kaiser-AV) within the discontinuities can have a significant impact on the overall material behaviour and slope stability performance. This explanation may be supported by the work conducted by Goodman, 1979 (Selby, 1993) indicating that the strength and stiffness of a filled discontinuity or joint decreases when the shear strength of the filling is less than it is for the joint material.

7. Types of Mass Movements

The most common mass movements in Brazil have been identified by Filho and Wolle (1996), which are creep, slides/ slips, falls and flows. Slips can be classified as translational or planar, circular or rotational, and wedge failure. Fall processes can be identified as falling blocks, block tipping (i.e. topples) and displacement. This description of landslide types is similar to the widely accepted schemes such as Hungr et al., 2014.

This is a pre-print of an article published in Geotechnical and Geological Engineering. The final authenticated version is available online at: https://doi.org/10.1007/s10706-019-01054-1.

Translational landslides in soil frequently occur on Brazilian mountains and hills, dominated by poorly developed soils and high slopes. They may be associated with saprolite soils and rock with weaknesses related to diverse geological structures. However, falls involve small volumes of rock, associated with steep slopes or excavations, such as rock cuts and quarries' walls (Brasil, 2004).

In the city of Caxias do Sul there are only a few records identifying the types of previous mass movements. However, recent evaluations carried out for the city council indicate a predominance of the translational slip process and, more rarely, falls (fractured rocks with conjugate pattern), bearings (blocks of rocks moving in soil matrix), block tipping (**Figure 9-a**) and wedges (**Figure 9-b**). Azambuja et al. (2001) classified two historical cases of mass movements in Caxias do Sul. The first was identified as a conjugate translational movement of a rocky mass according to a discontinuity plane filled with saprolite soil. This slope failure caused damage to a school and seven buildings. This movement was initially identified four years before the incident; the rate of movement increased during the periods of heavy precipitation (Azambuja et al., 2001). The second case was recognised as block tipping, due to the relief of lateral stresses on the slope. The block tipping occurred in the middle and upper part of the slope, which presents saprolite soils and more cohesive materials (Azambuja et al., 2001). Other studies were performed in the urban area and identified the occurrence of falling instability and slope block drop (Pontel et al., 2013, Baiotto et al., 2015).

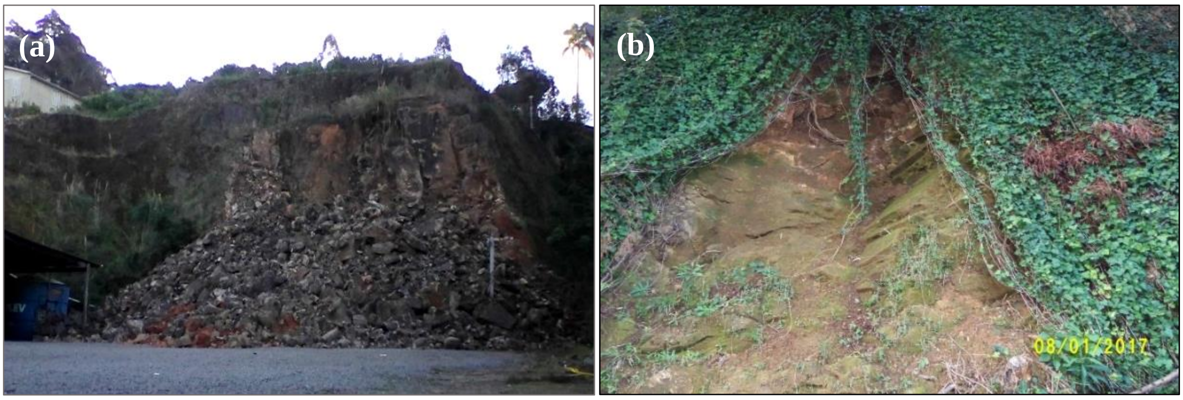

Fig 9. Two types of slope failure observed in Caxias do Sul: (a) Block tipping (b) Wedges failure

8. Landslide risk assessment

The main landslide risk assessment carried out for the urban areas of Caxias do Sul was conducted in 2006 (Profil, 2006). However, only a small fraction of the measures recommended in the report has been implemented. Since 2006, the urban area of the municipality has significantly expanded and the population has increased in areas which had been identified with medium to high risk as well as over new unclassified areas. The new urbanisation usually occurs in an unplanned and irregular way, without minimal infrastructure and on areas susceptible to natural disasters.

The expansion of the risk map of the city considered the nomenclatures areas of risk (i.e. area susceptible to destructive processes) and Risk Sector (sub-area within a risk area, including a subdivision according to the type of risk). The geotechnical risk assessment took into account the soil type and slope of the land. The geotechnical parameters of shear strength of the soils found in the region (Ana Rech, Forqueta, Caxias / Carijó, Canyon and Galópolis) have been estimated (**Table 4**) based on the existing geotechnical data and testing (Rigo, 2005; Perazzollo, 2003; Bressani *et al*, 2001; Azambuja *et al*, 2001; Soares *et al*, 2001, Pinheiro *et al*, 1997; Abramento and Pinto, 1993).

Table 4. Statistical analysis of shear strength parameters of some soils of the Serra Geral Formation (after Profil, 2006).

Soil Group	Estimated Parameters				Classification
	Effective friction angle, ϕ' (°)		Effective cohesion, c' (kPa)		
	Average	Standard Deviation	Average	Standard Deviation	
Galópolis	19	10	15	10	Plastic - Silt
Ana Rech and Caxias Carijó	33	9	30	25	No Plastic
Canyon and Forqueta	20	12	7	7	Plastic - Silt

The stability assessment has been determined based on parametric slope stability analyses. For a slope of 20 meters height, the slope face angle was varied, and the minimum safety factor was determined at failure. The height of the slope used in the model (20 meters) was chosen for two reasons: (i) because it represents the typical height of slopes in the city of Caxias do Sul and (ii) due to the accuracy of the survey provided for the work (Profil, 2006).

In order to consider the variability of the parameters of shear strength, presented in **Table 4**, the Monte Carlo probabilistic method has been used, by applying the variation of the parameters affecting the critical slip surface. In this analysis, the pore-water pressure effect was also considered, using the pore-pressure ratio R_{u1}, whose mean value was 0.1, with a standard deviation of 0.1. The product generated by the analysis consisted of the probability of failure curves versus slope inclination for each type of soil. **Figure 10** shows the results for slopes made of Galópolis soil.

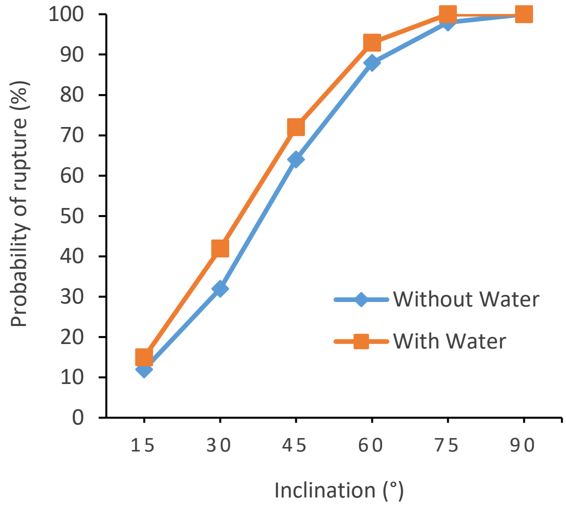

Fig 10. The variation of the probability of rupture (slope failur) using the parameters adopted for Galópolis soil. (based on data extracted from Profil, 2006).

Depending on the slope inclination, three categories of probabilities were defined: (i) High: the probability of slope failure is greater or equal to 50%, (ii) Average: the probability is between 25% and 50%, and (iii) Low: the probability is less than or equal to 25%. The critical slope inclination angles obtained for each type of soil are presented in **Table 5**.

Table 5. Probability of slope failure in relation to slope angle and soil type (for typical slope height of 20 m) (source of data: Profil, 2006).

Soil Group	Slope inclination		
	Low	Average	High
Galópolis	< 20°	20° - 35°	> 35°
Ana Rech and Caxias Carijó	< 45°	45° - 65°	> 65°
Canyon and Forqueta	< 17°	17° - 30°	> 30°

This work has also considered the history of slip occurrences including the verification of 345 cases in the field and developed their risk rating based on two factors: (i) probability and (ii) impact (or consequence). The probability was based on the methodology adopted by the Ministry of Cities of Brazil and the Technology Research Institute of São Paulo State

(2004). After the occurrence's probability is assessed, the potential impact of slope failure is determined according to its effect on the existing dwellings (e.g. houses) and infrastructures as explained in **Table 6**.

Table 6. Levels of potential impact of slope instabilities (after Profil, 2006).

Level of consequences	Affected dwellings	Affected infrastructure
High	more than 15	severely affected
Medium	from 5 to 15 dwellings	moderately affected
Low	from 1 to 5	slightly affected

Risk Rating is determined by crossing the information of the probability and the potential impact generated by the event. The range of values of Risk Rating is shown in **Table 7**, which defines a scale between 1 and 12 (1 being the lowest risk and 12 the highest).

Table 7. Risk Rating used in Caxias do Sul (after Profil, 2006)

Probability	Potential impact	Risk Rating
R1 (Low)	Low	1
	Medium	2
	High	3
R2 (Average)	Low	4
	Medium	5
	High	6
R3 (High)	Low	7
	Medium	8
	High	9
R4 (Very High)	Low	10
	Medium	11
	High	12

The risk assessment identified 184 sites within the urban perimeter of Caxias do Sul, subject to landslides and flood events, of which 163 were considered at risk of landslide, 20 per flood and one suffers both types of risks (Profil, 2006). **Figure 11** shows the number of areas identified for each Risk Rating (from 1 to 12), where more than 60% of the 163 areas affected by landslides have Risk Rating between 6 and 12.

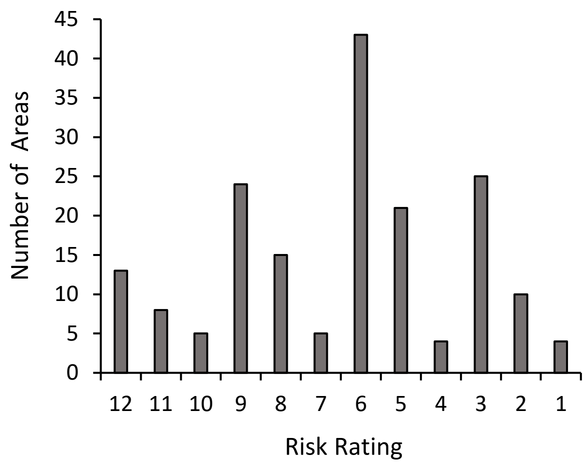

Fig 11. The number of areas identified vs Risk Rating in Caxias do Sul.

9. Discussion on factors affecting slope stability and recommended measures

Several site visits were conducted by the authors in September 2017 to approximately 14 different sites inside and outside the city of Caxias do Sul to carry out further visual inspect of the existing slope failures. It can be concluded from this recent field study as well as the available information (presented above) that the stability of the slopes in Caxias do Sul are largely affected by three main factors, discussed as follow:

9.1. The topography of the city and unplanned urban expansion

The city is dominated by mountainous topography with wide variation of slope angle which can reach as large as 90 degrees. Despite this intense topography, significant amount of houses have been self-built. This unplanned urban expansion is mostly associated with some casual slope cuts which might have increased the rate of deterioration of stability condition. To reduce the risk posed by this problem, it is recommended that planning permission is restricted on any slope without proper geotechnical investigation and risk assessment.

However, the latest official risk map (conducted by Profil, 2006) is now out of date as the urban area of Caxias do Sul has significantly expanded over the last ten years. The significant increase of buildings has changed the context of geotechnical risk. New geohazard mapping at the scales adopted in the existing map is essentially required. The new risk map could indicate more locations requiring urgent interventions for engineering works or slope stability monitoring. For long-term planning, it is suggested that a dedicated municipal team of technicians be trained to carry out monitoring and evaluation of areas prone to a landslide so that similar situations experienced by the Kaiser neighbourhood could be monitored and when necessary an action plan could be implemented to avoid any tragic accident. This team would also be responsible for keeping the risk map up to date and assessing which technologies would be most appropriate for monitoring slope condition for each specific case. Some affordable technologies such as radar, laser scanners and Unmanned Aerial Vehicles (UAVs or so-called drone), are efficient in the identification and monitoring of landslides particularly in difficult topography. The UAV technology is expected to become more widespread due to cost reduction (Rocca, 2016) and remarkable improved sensing capabilities. This technology would create an excellent opportunity for Brazilian local authorities to improve the current inspection and monitoring practice of vulnerable areas.

9.2. Geology of the city

Rocks and soils outcrop throughout the city. The rock has geological discontinuities (faults and fractures) filled with clays in many places. The stability of the rock slopes is significantly influenced by the structural discontinuities and their in-filling materials (Selby, 1993). The discontinuities observed during the site visits appear to control the type of failure which has occurred in the past. Observations suggest that such failure will continue. The properties of discontinuities such as orientation, persistence, roughness and infilling play an essential role in the stability of jointed rock slope and should be considered in the stability assessment. In critical places, it is highly recommended to monitor the rock slopes using the techniques that have been successfully implemented in other places in Brazil (Calvello et al 2015).

Soft soils with high plasticity has been also observed and exhibited seasonal volumetric change and ensuing downslope movement, particularly creep where slope angle is relatively small (less than 15º) and localised circular failure where slope angle is larger than 20º.

Despite the effort made by the local authorities and federal institutions to quantify the geotechnical parameters of the studied areas, it is still necessary to obtain more data (particularly about the plastic soils) to reduce the uncertainty of the identified values and inform the geotechnical models demonstrating safety factors of the vulnerable slopes in the region. In general, more geotechnical studies on rocks and soils, concerning their geotechnical characteristics, spatial properties and layout of the discontinuities, will add key information for geohazard mapping.

9.3. Rainfall and Sewage water

In all visited sites around the city, there is evidence that water has played an important role in the degradation of slope stability. The lack of proper drainage system for the rainfall and sewage water might have affected the slopes in different ways. Groundwater exists below the surface can generate pore-water pressure. A similar effect might be caused by the rainwater infiltration that seeps through surface and flows along the slope generating water pressure (Cai and Ugai, 2004). Elevated water pressure can reduce the effective stress and impact the shear strength of slope materials. The landslides' records shows (**Figure 2**) that the largest concentration of such events took place in the months of June, July and August, coincident with the highest period of precipitation in the region. To address this risk, drainage system is essential to reduce water pressure and thus enhances the stability of slopes.

10. Conclusion

Slope stability issues encountered in the city of Caxias do Sul were presented to demonstrate the existing situation of landslide risk assessment in southern Brazilian. Gaps in geotechnical information and outdated risk assessment were encountered.

Despite the effort made by the local authorities and federal institutions to quantify the geotechnical condition of the studied areas, it is still necessary to obtain more data (particularly about the high plasticity soils) to reduce the uncertainty of the identified values and to inform the geotechnical models of slopes' stability.

The experience from Caxias do Sul showed that the landslide risk assessment works were not adequately considered for the development of the city, largely because the geohazard map developed for the city has not been updated since 2006. In addition, there is currently no monitoring system adopted to observe the active slopes and identify the types of mass movements. Landslide risk assessment does not effectively contribute to risk's reduction unless the assessed areas are monitored and updated regularly to cover both the planned and unplanned urban expansion. New geohazard mapping is essentially required for the city supported with further research to identify other challenges facing the effective management of landslide risk.

Acknowledgements

The work was funded by the Newton Researcher Links (Ref. NRCP1617/6/182) administrated by the Royal Academy of Engineering (RAEng). The authors would also express their gratitude to the Autonomous Municipal Water and Sewage Service of the Municipality of Caxias do Sul for their kind support.

References

Abramento, M., Pinto, Cs., 1993. Resistência ao cisalhamento de solo coluvionar não saturado das encostas da Serra do Mar. Solos e Rochas, v. 16, n. 3, p. 145-158.

Agência Brasil. 2014. Moradores atingidos pela enchente de 2011 não vivem clima de Copa em Teresópolis. In: http://agenciabrasil.ebc.com.br/geral/noticia/2014-05/moradores-atingidos-pela-enchente-de-2011-nao-vivem-clima-de-copa-em

Argenta, G., Kormann, T.C., Robaina, L.E.S., 2009. Levantamento da ocorrência de desastres naturais no município de Caxias do Sul – RS. In: Simpósio Brasileiro de Geografia Física Aplicada. Anais... Viçosa, 2009.

Azambuja, E., Nanni, A.S., Bressani, L.A., Rigo, M.L., 2001. Casos históricos de dois movimentos de rochas em encostas associadas à Formação Serra Geral. In: Conferência brasileira sobre estabilidade de encostas, 3., 2001, Rio de Janeiro. Anais... Rio de Janeiro: ABMS, p. 271-278.

Baiotto, C.Z., Pereira, I.V., Visentin, J.M., Alberti, K., Boff, F.E., 2015. Áreas de risco devido a declividade de taludes e eventos pluviométricos: Estudo de caso na cidade de Caxias do Sul. Atividade de Pesquisa Supervisionada (APS). Faculdade da Serra Gaúcha (FSG).

Brasil., 2004. Manual de treinamento de técnicos municipais para o mapeamento e gerenciamento de áreas urbanas com risco de escorregamentos, enchentes e inundações. Ministério das Cidades (Ministry of Cities of Brazil), IPT (Technology Research Institute of the São Paulo State) CPRM/SGB, Rio de Janeiro. (193 pp.).

Bressani, L.A., Bica, A.V.D., Pinheiro, R.J.B., 2001. Residual shear strength of some tropical soils from Rio Grande do Sul. Solos e Rochas, v. 24, n. 2, p. 103-113.

Bressani, L.A., Flores, J.A.A., Nunes, L.F., 2005. Relatório e Mapa Final. Contrato nº. 2615.000386-97/2004. Programa Habitar Brasil. Desenvolvimento de estudos de engenharia geotécnica/geologia com vista à geração de relatório e mapa geotécnico dos solos e rochas superficiais da área urbana da cidade de Caxias do Sul.

Cai, F. and Ugai, K., 2004. Numerical analysis of rainfall effects on slope stability. International Journal of Geomechanics, 4(2), pp.69-78.

Calvello M., d'Orsi R.N., Piciullo L., Paes N., Magalhaes R., Lacerda W.A (2015). The Rio de Janeiro early warning system for rainfall-induced landslides: analysis of performance for the years 2010–2013. International Journal of Disaster Risk Reduction, 12:3-15.

Camargo, A.P., 1991. Classificação climática para zoneamento de aptidão agroclimática. Viçosa, MG. UFV.

CPRM - Brazilian Geological Survey, 2010. Geodiversidade do Estado do Rio Grande do Sul. Programa Geologia do Brasil. Ministério de Minas e Energia.

Craig, R.F., 2004. Craig's soil mechanics. p447. 7th ed. 2004.

De Espindola, G.M., da Costa Carneiro, E.L.N. and Façanha, A.C., 2017. Four decades of urban sprawl and population growth in Teresina, Brazil. Applied Geography, 79, pp.73-83.

Filho, O.A., Wolle, C.M., 1996. Cartas de risco de escorregamentos: uma proposta metodológica e sua aplicação no município de Ilha Bela, SP. São Paulo: ABGE, Revista Solose Rochas, v.19, n.1, p.45-62.

Hungr, O., Leroueil, S. and Picarelli, L., 2014. The Varnes classification of landslide types, an update. Landslides, 11(2), pp.167-194.

IBGE - Brazilian Institute of Geography and Statistics, (2010). Censo demográfico de 2010. Rio de Janeiro. Disponível em: https://ww2.ibge.gov.br/cidadesat/xtras/perfil.php?lang=&codmun=430510&search=rio-grande-do-sul|caxias-do-sul. Acesso: 14 April 2018.

Lisboa, N.A., Remus, M.V.D., Dani, N., Castro, J.W., Neto, F.T., 2003. Estudo geológico e hidrogeológico para o aproveitamento de água do Aquífero Guarani no Município de Caxias do Sul. Relatório Final. Caxias do Sul, p.72.

Marques, J.A.P., 2011. Estudo de metodologia de avaliação de risco a escorregamento de terra em área urbana : o caso do município de Juiz de Fora - MG / Janezete Aparecida Purgato Marques. – 2011. 144 f.: il. Dissertação (Mestrado em Ambiente Construído)– Universidade Federal de Juiz de Fora, Juiz de Fora.

Perazzolo, L., 2003. Estudo geotécnico de dois taludes da Formação Serra Geral, RS. Porto Alegre. Dissertação (Mestrado em Geotecnia) - Programa de Pós-Graduação em Engenharia Civil, Universidade Federal do Rio Grande do Sul.

Pinheiro, R.J.B., Bressani, L.A., Bica, A.V.D., 1997. A study on the residual shear strength of two unstable slopes in the state of Rio Grande do Sul. In: Panamerican symposium on landslides, brasilian conference on slope stability, 1997, Rio de Janeiro. Anais... Rio de Janeiro: ABMS, 2v., v. 1, p. 443-452.

Pontel, A.L., Stefani, A., Bedinot, J., Morelatto, S., Boff, F.E., 2013. Avaliação da condição de instabilidade de taludes com determinação de medidas de contenção. Atividade de Pesquisa Supervisionada (APS). Faculdade da Serra Gaúcha (FSG).

Profil Engenharia E Ambiente., 2006. Plano Municipal de Redução de Risco para o Município de Caxias do Sul. Programa: Urbanização, Regularização e Integração de Assentamentos Precários. Contrato de Repasse nº 0164957-13/2004. Mapeamento de Risco Relatório Parcial - Etapa 2A. Setembro/2006.

Rigo, M.L., 2005. Mineralogia, Intemperismo e Comportamento Geotécnico de Solos Saprolíticos de Rochas Vulcânicas da Formação Serra Geral. Tese de doutorado. Porto Alegre: PPGEC/UFRGS, 348 p.

Rocca, R., 2016, April. Low cost 3d mapping using a commercial drone/UAV: Application in structural geology. In International Conference and Exhibition, Barcelona, Spain, 3-6 April 2016 (pp. 143-143). Society of Exploration Geophysicists and American Association of Petroleum Geologists.

Roisenberg, A., Viero, A.P., 2000. O vulcanismo Mesozóico da Bacia do Paraná no Rio Grande do Sul. In: HOLZ, M.; DE ROS, L. F. (Org.). Geologia do Rio Grande do Sul. 2ª ed., Porto Alegre: Editora da UFRGS, V. 01, p. 355-374.

Selby, M. J. 1993. Hillslope materials and processes. 2nd edition. Oxford: Oxford University Press, pp. 87-89.

Shi, P., Xu, W., Ye, T., Yang, S., Liu, L., Fang, W., Liu, K., Li, N. and Wang, M., 2015. World atlas of natural disaster risk. In World Atlas of Natural Disaster Risk (pp. 309-323). Springer Berlin Heidelberg.

Soares, J.M.D., Pinheiro, R.J.B., Maciel Filho, C.L., Robaina, L.A., Bica, A.V.D., Bressani, L.A., 2001. Estudo da estabilidade de encosta em área urbana no município de Santa

Maria – RS. 3ª Conferência Brasileira sobre Estabilidade de Encostas (COBRAE), Rio de Janeiro. Anais: ABMS, p. 199-206.

Souza, L.A., Sobreira, F.G., 2014. Guia para elaboração de cartas geotécnicas de aptidão à urbanização frente aos desastres naturais. 68 pag. ISBN: 978-85-917793-0-7.

Wiggers, M.M., Robaina, L.E.S., 2014. Zoneamento das áreas de risco a movimentos de massa na área urbana do município de Caxias do Sul (RS). Bgg 41, v. 1 - págs. 260-279 - Jan. de 2014.