Review Paper

Risk assessment on landslides focused on the role of the water: examples from model regions (Rio de Janeiro State and Hong Kong)

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Abstract
Landslides are one of the most vital natural hazards on Earth. To satisfy the demand for protection against landslides, it is necessary to systematically assess and manage landslide hazards and risk. Landslide mechanisms related to hydrology are analyzed with focus in the major risks, and formal risk assessment methodologies are presented in the paper. Issues related to risk assessment are discussed and different steps are described. The management of accidents in slopes is discussed, with particular emphasis to Hong Kong and Rio de Janeiro in Brazil. Hong Kong is a region of China with a large population density and very mountainous. There is a history of tragic accidents in the slopes. The territory has a tradition of a high standard in the practice of slope engineering. The establishment of an efficient security system developed by Geotechnical Engineering Office was established in the territory. Also, specific aspects of slope instability in the state of Rio de Janeiro are discussed, and in Rio de Janeiro city, with focus on cases which occurred in the mountainous region of the State. The mega-disaster that occurred in 2011, with high number of deaths and significant economic losses, is studied with incidence in individual landslides.

Keywords Natural hazards · Hydrological risk · Groundwater · Landslides · Earthquake

1 Introduction

Landslides are one of the most important geotechnical risks on planet Earth. Landslides are hard to predict because their initiation depends on many factors and on the interaction between these factors. To satisfy the societal demand for protection against landslides, it is necessary to systematically assess and manage landslide hazard and risk. This can be done using principles of decision making under uncertainty (e.g., [33, 82]).

Natural or built slopes are defined as sloping surfaces on rock masses, earthy or mixed masses, originated from geological, geomorphological processes and anthropic actions. The slope design involves the collection of geological and geotechnical information, the evaluation of the strength properties of the formations and discontinuities, and of the presence of water with emphasis on the pluviometry regime (e.g., [2, 9, 17, 33, 54, 70, 74, 76, 81, 92, 96]).

The presence of water is one of the major triggers for the landslides or rock stability. The hydrologic response of a slope to rainfall depends on a great number of factors, on both local and catchment basin scales [54]. In fact, the percolation of water into the discontinuities induces a pressure increase on the adjacent rock surfaces and promotes the decrease of the shear strength of these surfaces [41, 92]. The hydrologic response of a slope to rainfall is a

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complex phenomenon. As it rains on a slope, some of the incident water will infiltrate in the slope, which depends on the rainfall characteristics and of the hydraulic properties of the ground, rock mass or soil formations. Since the ground near surface is usually unsaturated, the infiltration process involves flow also thorough the unsaturated zone [12, 54].

The presence of groundwater in rock slopes may have a detrimental effect for several reasons among others (e.g., [4, 10, 17, 41, 69, 96], as follows: (1) water pressure reduces the stability of the slopes by decreasing shear strength of potential failure surfaces [48], (2) changes in the contents of some rock formations can increase weathering and consequently decrease shear strength [42, 68], (3) erosion of weathered rock can result in local instability by surface water [72] and (4) in cold weathers the freezing of the groundwater can cause wedging due to temperatures volume changes in the ice and also can block drainage paths [96].

Groundwater in rock slopes is often a primary cause of instability; therefore, in general, the reduction in water pressures is favorable to the stability of the slope by performing drainage works. The usual methods of the reducing the water pressure include several measures such as limiting surface infiltration of rainfall, drilling horizontal drain holes, or executing drainage adits at the toe of the slope [7, 96]. Therefore, the decision to be taken depends on the rainfall intensity, of the permeability of the ground and of course of the dimensions of the slope [76].

The design of a slope requires a systematic collection of geological, geotechnical and hydraulic data, as well as the evaluation of the resistance properties, the definition of the discontinuities network and the presence of the water [15, 17, 41]. For slope movements, there are several classifications (e.g., [12, 65]).

Certain regions can be affected by several geohazards and natural disasters that include earthquakes, volcanic eruptions and extreme meteorological events. Earthquakes, particularly those with strong ground motion, can trigger thousands of landslides in mountainous regions with unfavorable geomorphic environments. The 2008 Wenchuan earthquake which occurred in China is such an example. More than 87,000 casualties and millions of displaced people were reported in an area of about 850 km^2 affected by the earthquake. The major landslides were distributed along the Longmenshan fault. Among the most significant landslides, the Daguangbao landslide was the largest in volume [44, 51].

The systematic risk assessment and management in slopes is essential to ensure the safety of such systems. The risk assessment begins with the site selection. During the design and planning stages, it is necessary to evaluate risks associated with the geology and to obtain information on

site that provides the input necessary for the risk assessment evaluation. The stage related to the identification and description of threats will be the next step, in order to evaluate risks and the formal incorporation of uncertainties in the slope issue. Risk identification models, in particular regarding instability mechanisms, can be deterministic and probabilistic ones [1, 54]. The identification and description of accidents in slopes are very important, with the collection of information on movements and geometry of accidents. The establishment of databases with accidents and their structuring aiming the application of Data Mining techniques (DM) and the direct description of the instability of slopes is processed to analyze the risk. Special focus is given to various DM techniques, with special emphasis on Neuronal and Bayesian Networks (BN). The use of the probabilistic techniques of BN is relevant to manage the risk, and sensitivity analyses are recommended. The application of a BN to a decision problem in slope instability is well illustrated in Einstein and Sousa [33]. Risk assessment and risk management for slopes require as initial step the identification of the threats that are possible which can lead to detrimental consequences. The major threats are in general associated with precipitation, subsequent infiltration and groundwater flow [83, 84]. The occurrence of earthquakes can be very relevant as a triggered factor [44].

The risk management practice is a relevant activity in certain regions, like in Hong Kong territory and in the city of Rio de Janeiro. Honk Kong is a region with a large population density and very mountainous. Therefore, there is a history of tragic accidents in the slopes. The territory got a tradition of a high standard in the practice of slope engineering. The establishment of an efficient security system developed by Geotechnical Engineering Office (GEO) was established in the territory. In each year, GEO reported hundreds of slope instabilities, whose data are stored on a database, being the large majority relatively small although larger slips occur. It introduced a long-term program to systematically analyze the slopes of government works and perform a safety analysis of private works. Maintenance programs were established by the various governmental sectors. The definition of risk reduction strategies is one of the most relevant activities being developed to avoid or eliminate certain accidents and includes stabilization, mitigation; this is a reduction of vulnerability, and the establishment of warning systems (e.g., [20, 47, 67, 83, 84]. Detailed risk analyses are made consistently in the territory, as well as the establishment of guidelines for the study of accidents.

The city of Rio de Janeiro is another important situation in terms of hydrological risks. The occupation of hills and slopes throughout its history has been promoted. The occurrence of serious geotechnical accidents,

particularly of falling blocks, derives from its unique and complex geographic and morphological characteristics. The studies conducted through surface mapping showed a high susceptibility to rock falls. Sometimes, there have been observed effects of temperature variation during dry periods, and interpretative models originated in thermal actions were proposed [94]. In consequence, several containment works have been carried out. An Institute was created, now named GeoRio Foundation. Its creation occurred after severe rainy events that occurred in the city in 1966. Since then, the technical staff formed by engineers and geologists conducts surveys and defines the necessary works to ensure the safety of the population. Geo-Rio has implemented the Rio Alert system, which maintains pluviometry stations scattered throughout the city to monitor the rains. A radar is located in Sumaré, and its images are updated every two minutes and allow observing the location, displacement and intensity of precipitation.

A case situation in Rio de Janeiro State is presented, where natural disasters occurred in the mountainous region of the State. Specific aspects of slope instability are discussed, with focus on cases which occurred in the mountainous region of the State. A mega-disaster happened in 2011, with high number of deaths and significant economic losses, and is studied with incidence in individual landslides. Heavy rains which caused floods and landslides in seven municipalities were considered the largest climatic and geotechnical catastrophe of Brazil, identified by the United Nations as the eighth largest landslide in the world in the last 100 years [13, 83, 84].

In this study, landslide mechanisms related to hydrology are analyzed with focus in the major risks, and formal risk assessment methodologies are presented. In Sect. 2, concepts concerning the problem of risk management in slopes are also highlighted. The existing experience in Hong Kong is reported, as well in Rio de Janeiro city, and emphasized in Sect. 3. Specific aspects of slope instability occurring in the State of Rio de Janeiro with incidence in the mountainous region are discussed in Sect. 4. Concluding remarks are finally presented.

2 Hydrological risk and risk assessment

2.1 Hydrological risk concepts

The hydrological behavior of a slope is very complex, particularly to rainfall, and depends on a great number of factors in the local and catchment area (e.g., [12, 54, 76–78, 96]. Some of these factors are illustrated in Fig. 1. Water is one of the major triggers of landslides. Different effects that water has on slope stability are described in detail in the publications of Wyllie and Mah [96] and Bronnimann [12].

When it rains on a slope, some of the infiltrated water will infiltrate into the slope. The distribution of this water will depend on the rainfall characteristics and of the hydraulic properties of the soil. The bedrock is often considered to be an impermeable surface below the soil. However, different studies showed that bedrock permeability can control the hydrological regime of the catchment [12,

Fig. 1 Factors affecting hydrologic response of slopes to rain [54]
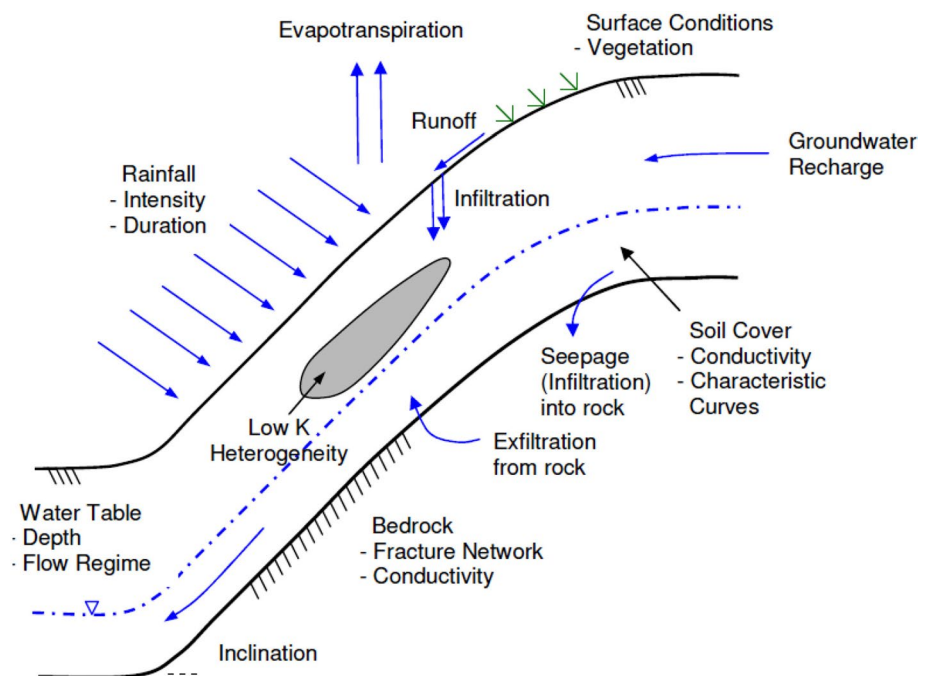
58, 78]. Soil near the ground surface is usually unsaturated and consequently the process of infiltration is related to the flow through unsaturated media. The unsaturated soil shows great special and temporal variations with changes in moisture content [54]. In saturated soils, the moisture content is equal to the porosity of the soil. The hydraulic conductivity of the soil is assumed to be a function of the depth.

Landslides belong to the most frequent natural hazards all over the world. Important geomorphological features of a landslide are indicated in Fig. 2. Landslides can be secondary natural hazards triggered by earthquakes, volcanic eruptions in combination with earthquakes, or flood events. A catastrophic situation occurred while the Wenchuan earthquake occurred in China [44].

Various models have been developed to estimate the rate of infiltration from single one dimension to three dimensions using finite differential and finite element models [37, 54]. Landslide hazard assessment relies on modeling. Models include solutions for hydrologic and stability analysis. Figure 3 shows possible modes used in hydrology. Possible models for stability analysis can be documented in Karam [54]. The issue of model uncertainty is very relevant for both types of analysis (e.g., [31, 33, 62]).

The hydrological models are models for the trigger, i.e., rainfall, as well as models to describe what happens when the water enters in the soil. Rainfall models comprise characterization models for the characterization of a particular rainstorm and models for predicting the occurrence of storms [54]. Water flow in in rock masses occurs mainly along the discontinuities. The flow through rock masses, at macroscopic level, can be considered following a continuous or a discontinuous model one in which laminar flow can be considered (e.g., [10, 69, 96]).

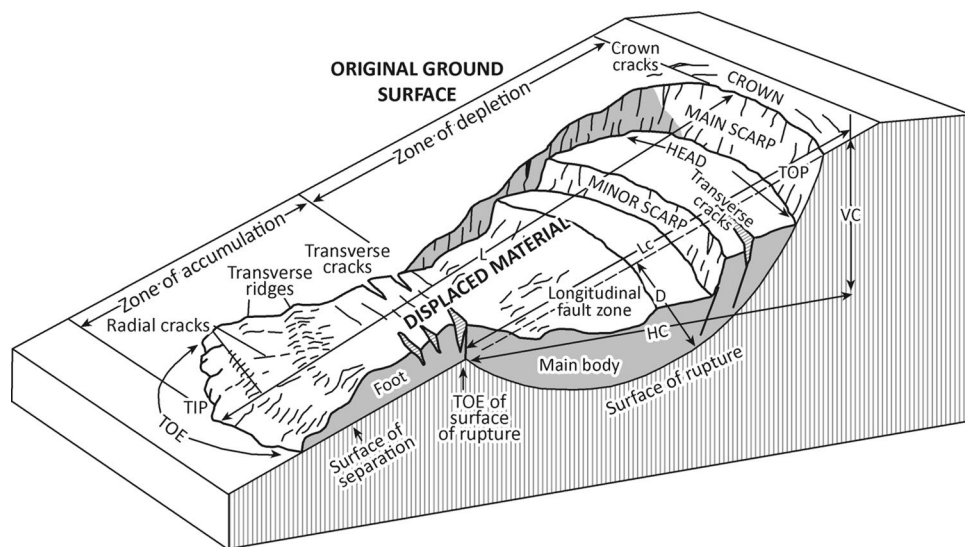**Fig. 2** Important features of a landslide [22]

Fig. 3 Hydrological models for slopes

Hydrological Models			
Rainfall	**Characteristics Curves**	**Infiltration**	**Subsurface flow**

Mean intensity and duration
- Sinusoidal
- Exponential
- Extreme type
- Others
	- Saturated soil
	- Nonsaturated soil
	- Moisture retention curve
	- Hydraulic conductivity curve
		- Saturated (Darcy)
		- Saturated / Unsaturated
		  o Analytical
		  o Numerical (FEM.FDM)
		  o Philips
		  o Others
			- Soil
			  o Saturated
			  o Saturated / Unsaturated
			  o Analytical
			  o Numerical
			- Rock
			  o Continuum
			  o Discontinuum
			- Catchment
			  o Water balance

2.2 Risk assessment

Risk can be expressed in many ways. Thus, risk can be expressed as [33, 54, 55, 85]:

$$R = P[T] \sum_i P\big[C_i|T\big] u\,(C_i) \tag{1}$$

Table 1 Different level approaches (see Fig. 4)

Description
Assess state nature (L1)
Identify and describe the threat (L2)
Determine probabilities and combine with threat to determine hazards (L3)
Risk assessment (L4)
Risk managements (Decisions) (L5)
Information model (L6)

where R is risk, $P[T]$ is the hazard, defined as the probability that a particular threat occurs within a given period of time, $\sum_i P[C_i|T]$ is the vulnerability, defined as the conditional probability that consequences C_i occur given the threats C_i are consequences which can include for example economic damage, as well as those that affect human lives, such as injuries and fatalities, and $u(C_i)$ is the utility of consequences C_i, defined as a function that describes a decision-maker's relative preferences between attributes.

The steps or levels (Table 1) in the decision analytical approach are described in Fig. 4.

The level L1 is related to the information collection. Slope instability initiation is complex and depends on a great number of factors and the interaction between them (Fig. 1). The strength of a rock mass is affected by the rock strength and by the existence, and persistence of fractures and joint sets. Furthermore, the percolation of water has major effects on the stability, and subsurface flow regimes can be complex. In addition, natural events, such as rainfall and earthquakes, and manmade factors, such as blasting,
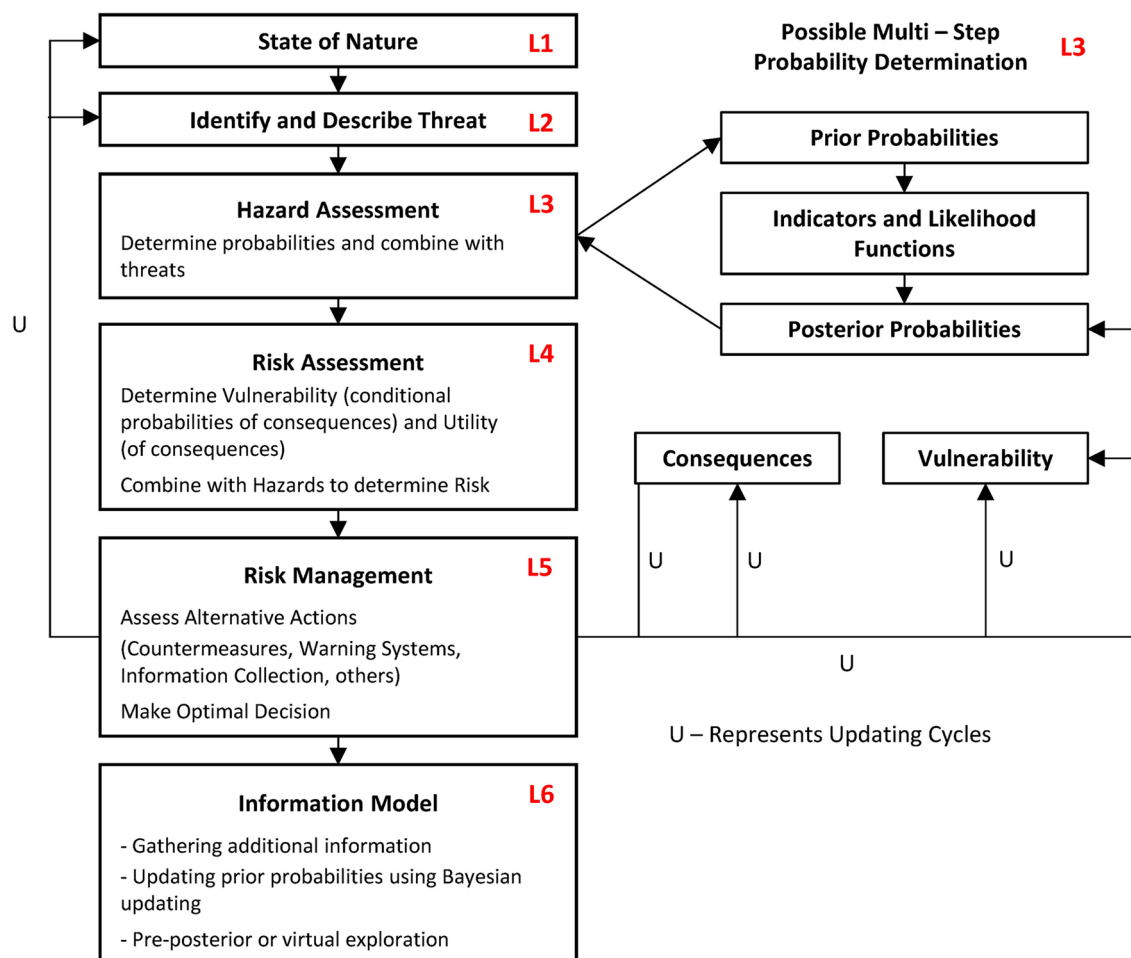

Fig. 4 Decision analytical approach to natural threat risk assessment and management (Adapted from [29]), see Table 1

can serve as triggers to slope instabilities [52, 55]. Collecting information on the parameters that affect slope stability, which means site characterization, is usually done through exploration schemes [91]. Typically, information may comprise traditional techniques such as maps, photographs, boring logs, topographical data, weather data and visual observations [8, 55, 91].

For level L2, there are various techniques to assess slope stability that range in complexity from simple to statistical models based on historical data, to more complex mechanical models which attempt to represent reality [54]. In rock masses, a typical mode of slope failure involves a block of material sliding on two or three planes of discontinuity, known as rock wedges. The stability analysis of wedges in rock slopes involves resolution of forces in 2D and 3D space. The methods used include structural geology diagrams (particularly, stereographic projection technique), engineering graphics, and vector analysis (e.g., [39, 49, 64, 65, 95, 96] and references therein).

Several categorizations of uncertainties have been proposed (Level L3) over the years and have been discussed in the context of slope stability risk assessment (e.g., [30, 31, 54, 61, 85]. The formal integration of uncertainties into the slope stability problem results in probabilities of slope instabilities or hazards. These can range in from first and second order reliability analyses (e.g., [24, 43], to full distribution probabilistic analyses based on numerical techniques (e.g., [40, 54, 66, 85, 93], and references therein).

Risk is obtained as combination of the quantified hazard with the quantification of consequences conditional on the hazard. For level L4 on risk assessment, it is worth noting that a particular hazard can have different consequences. The quantification of consequences requires the identification of consequences and associating an expression of loss with them. This expression is usually in the form of a utility function [5], which is a dimensionless transformation that describes the relative preferences of the decision-maker toward different outcomes, as well as the decision-maker's attitude toward risk, i.e., risk neutral versus risk averse [34, 50, 55, 59].

Level L5 is related to decisions. Decisions in the slope instability problem concern measures that can be taken to mitigate risk. These actions can range from construction countermeasures to administrative procedures. Typical actions include (1) passive countermeasures which include galleries and nets; (2) active countermeasures, including rock bolts, anchors, tie-backs and retaining structures; and (3) warning systems, which mitigate risk by reducing consequences. Warning systems consist of devices capturing relevant signals, models for relating the signal to potential threats, people and procedures interpreting the modeled results, evaluating consequences, and issuing warnings. Warning systems include the following components:

monitoring systems with data acquisition that track a threat such as slope instability; communication systems that continually transit measurements to experts; models that predict the threat in the short and long terms; alarm systems that transmit the warning signal(s) to the potentially affected parties efficiently and effectively when a predefined alarm threshold is exceeded; and specific actions (procedures) that are implemented during the warning, as well as those after the warning [55, 80].

Last level L6 involves the gathering of additional information. This involves updating prior probabilities to result in posterior probabilities that reflect the new information. This is usually done using Bayesian updating [85]. It is possible and often desirable to check whether it is worthwhile to collect additional information through the information modeling prior to going out and obtaining the information. This is done through the process of pre-posterior or virtual exploration. This process has been applied in the context of tunnel exploration planning in Karam et al. [56, 57], and for landslides in Einstein et al. [32].

Risk management is fundamental, and possible management actions were shown regarding no action, active and passive actions, as well as considering warning systems that can be considered as a type of passive countermeasure [33]. Possible management actions are shown in a decision tree represented in Fig. 5.

Countermeasures reduce the risk but adding costs. Passive countermeasures reduce the vulnerability, resulting in a reduced risk R', where:

$$R' = P[T] \times \sum_i P'[C_i|T] u(C_i) + u(C_{pas}) \qquad (2)$$

where $P'[C_i|T]$ is the reduced vulnerability and $u(C_{pas})$ is the utility associated with the cost of the passive countermeasure.

Active countermeasures reduce the vulnerability, resulting in a reduced risk R', where:

$$R' = P'[T] \sum_i P'[C_i|T] \times u(C_i) + u(C_{act}) \qquad (3)$$

where $P'[C_i|T]$ is the reduced probability of threat and $u(C_{act})$ is the utility associated with the cost of the active countermeasure.

Risk analysis can be of two types, qualitative and quantitative (e.g., [16, 65, 83, 84]). Qualitative analysis is faster and associates each event with analyzing a qualitative index, both for frequency and for the respective damage, being possible to represent the risk as a combination of frequency classes and damage classes. A risk matrix therefore makes it possible to establish the risk acceptability criteria and, in this way, determine the critical, noncritical events or those on which it is necessary to carry out more exhaustive assessments. The risk analysis is said to

Fig. 5 Decision tree slope instability with different possible actions [33]
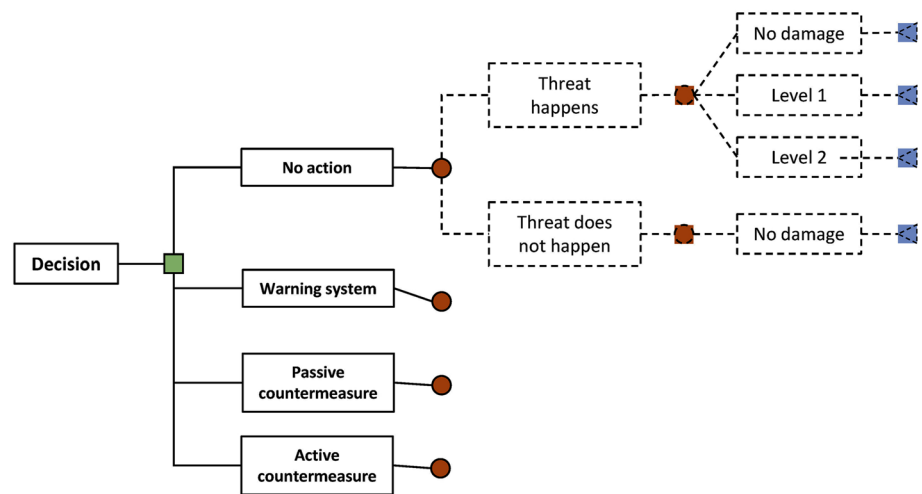
be quantitative when it is based on numerical values of the potential consequences and the probability of the occurrence of adverse events. This group includes analyses by event trees (ETA—Event Tree Analysis) and failure trees (FTA—Fault Tree Analysis). Possible slope management actions are illustrated in Fig. 5 using an event tree analysis.

The concept of risk map is widely used and results from the application of a previously defined risk classification to a geographical area. It is possible to assign to each point in the area under study the corresponding level (in the case of qualitative analysis) or numerical value (in the case of quantitative analysis) of risk, thus obtaining a risk map of the area over which the adverse events have the probability of occurring. In a risk map, the areas with the highest risk will be recognizable, where it will be advisable to intervene by applying mitigation measures [65]. The risk maps, based on new elements obtained through monitoring, can be recalculated and redesigned [14].

The methodologies followed for risk analysis and decision making are based, today, on the use of Artificial Intelligence (AI) techniques, including the use of DM techniques, such as knowledge-based systems, approximation of fuzzy rules, networks artificial neurons, event trees, fault trees, classic analysis decisions and Bayesian networks [21, 28, 86]. To define risk levels, countries or regions have adopted different attitudes. Some adopt the ALARP (As Low as Reasonably Practical) principle and define iso-risk values for new activities [33, 65].

Slope stability is a complex area that deals with data from nature (geology, morphology, hydrology, climatology, etc.) that are mostly scarce due to limitations of access and availability of information. Due to this limitation, it is necessary to use probabilistic methods in order to introduce uncertainties in the risk analysis and decision processes. BN are probabilistic dependency graphs for reasoning in conditions of uncertainty. The use of these models is becoming increasingly common in spatial problems such as the analysis of the risk of slope stability. The degree of involvement in spatial problems varies from the spatial mapping of results, to BN-based nodes that explicitly involve geographical characteristics, and the integration of different networks based on geographical information [36, 45, 75, 85, 86].

BN can be used at any stage of a risk analysis, and in the case of slopes, and can replace both fault and event trees in logical tree analyses [33, 86]. While the common cause or more general dependency phenomena represent significant complications in the analysis of the classic failure tree, this is not the case for BN. On the contrary, they facilitate the modeling of such dependencies. Because of what has been said, BN provide a good tool for decision analysis, including pre-analysis and post-analysis. In addition, they can be generalized to include influence diagrams and to be able to model decision making explicitly, including for such modules related to decision and utilities [86].

In the case of slope stability, the system exposure can be calculated using physical and (or) numerical models. In addition to determining risk maps, it is also possible to test the effect of various options through BN with decision nodes. The application of a BN to a decision problem in slope instability is illustrated in Fig. 6, where the effect of several measures including an evacuation warning system is tested. The matrices associated with the warning system (Alarm) are shown; danger (Threat); cost of measures to be taken (countermeasures); cost of measures (active, passive, warning systems); and cost of consequences [33]. The objective of the study and determination of the best intervention (or mitigation) measure to take (for example: alarm system with evacuation, anchorages (active), monitoring system, safety nets (passive) among others).

The result of the entire decision process to be taken is evidenced by the result obtained with the BN in Fig. 7. It
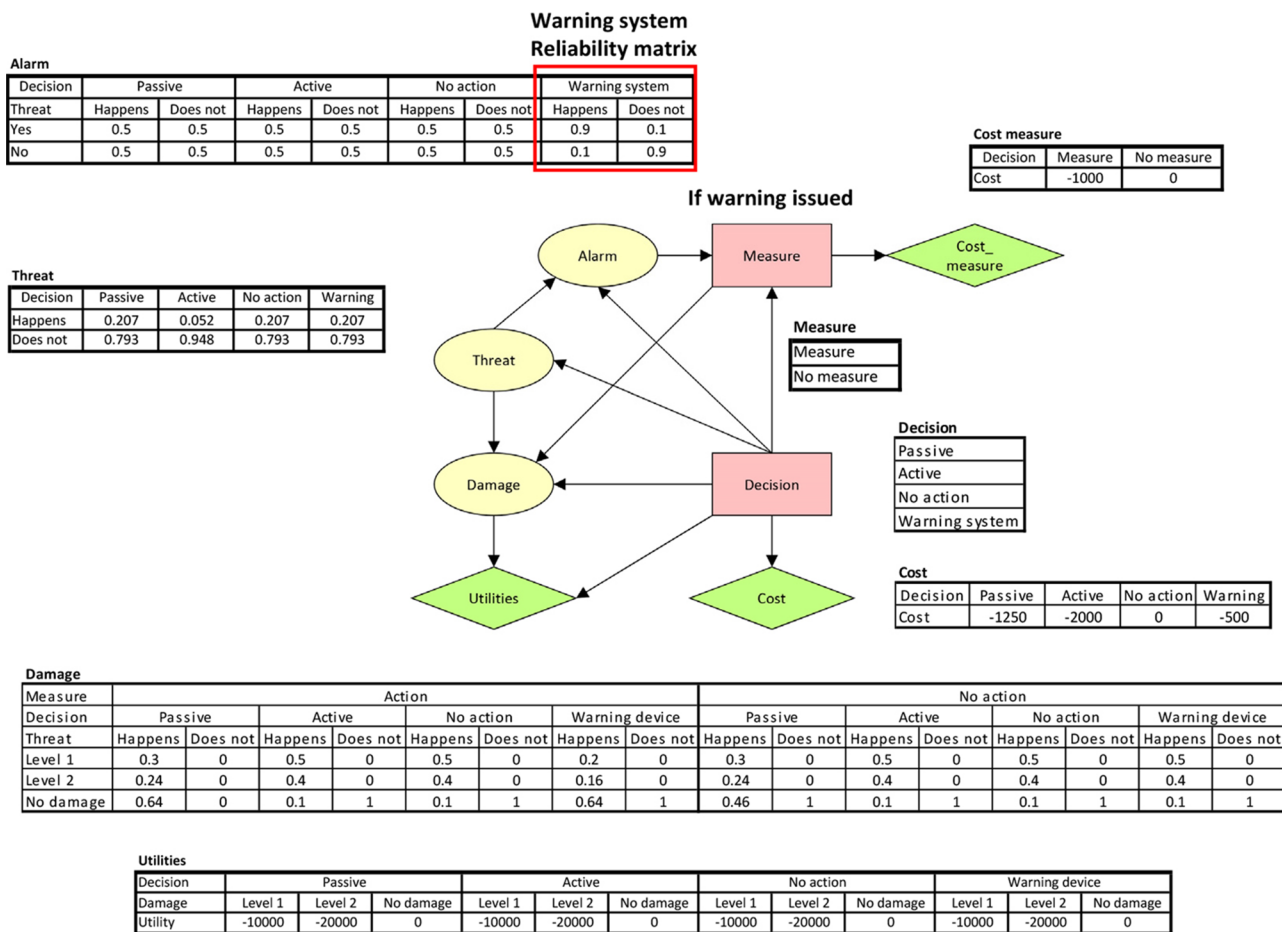
Warning system Reliability matrix

Alarm

Decision	Passive		Active		No action		Warning system	
Threat	Happens	Does not	Happens	Does not	Happens	Does not	Happens	Does not
Yes	0.5	0.5	0.5	0.5	0.5	0.5	0.9	0.1
No	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.9

Cost measure

Decision	Measure	No measure
Cost	-1000	0

Threat

Decision	Passive	Active	No action	Warning
Happens	0.207	0.052	0.207	0.207
Does not	0.793	0.948	0.793	0.793

If warning issued

Measure

Measure
No measure

Decision

Passive
Active
No action
Warning system

Cost

Decision	Passive	Active	No action	Warning
Cost	-1250	-2000	0	-500

Damage

Measure	Action								No action							
Decision	Passive		Active		No action		Warning device		Passive		Active		No action		Warning device	
Threat	Happens	Does not	Happens	Does not	Happens	Does not	Happens	Does not	Happens	Does not	Happens	Does not	Happens	Does not	Happens	Does not
Level 1	0.3	0	0.5	0	0.5	0	0.2	0	0.3	0	0.5	0	0.5	0	0.5	0
Level 2	0.24	0	0.4	0	0.4	0	0.16	0	0.24	0	0.4	0	0.4	0	0.4	0
No damage	0.64	0	0.1	1	0.1	1	0.64	1	0.46	1	0.1	1	0.1	1	0.1	1

Utilities

Decision	Passive			Active			No action			Warning device		
Damage	Level 1	Level 2	No damage	Level 1	Level 2	No damage	Level 1	Level 2	No damage	Level 1	Level 2	No damage
Utility	-10000	-20000	0	-10000	-20000	0	-10000	-20000	0	-10000	-20000	0

Fig. 6 BN applied to a rock slope instability problem [33]

ends with a decision on the final utilities for each of the actions and selects the one with the smallest (negative) utility, in this specific example and the alert system.

3 Management of accidents in slopes

3.1 General

Natural or constructed slopes are defined as inclined surfaces in rocks or soils, or mixed masses, originated from geological, hydrogeomorphological, and anthropic processes (Fig. 2).

In this section, risk management practice is described for Hong Kong region and for the city of Rio de Janeiro, describing their practice in management accidents in slopes. Hong Kong is a region of China with a large population density, in a territory of only 1100 km^2, and very mountainous. About 75% of the territory has slopes greater than 15°, and more than 30% has slopes greater than 30°. There is a history of tragic accidents in the

slopes. The territory has a tradition of a high standard in the practice of slope engineering. The establishment of an efficient security system developed by Geotechnical Engineering Office (GEO) was established in the territory. In each year, GEO reported hundreds of slope instabilities, whose data are stored on a database, being the large majority relatively small although larger slips occur, with more than 5000 m^3. A long-term program was also introduced to systematically analyze the slopes of government works and perform a safety analysis of private works. Maintenance programs were established by the various governmental sectors. The definition of risk reduction strategies is one of the most relevant activities being developed to avoid or eliminate certain accidents and includes stabilization, mitigation; this is a reduction of vulnerability, and the establishment of warning systems [67, 90]. Detailed risk analyses are made consistently in the territory, as well as the establishment of guidelines for the study of accidents.

Also, the city of Rio de Janeiro, Brazil, is another important municipality in terms of hydrological risks. The

Fig. 7 Decision making for a slope instability problem [33]
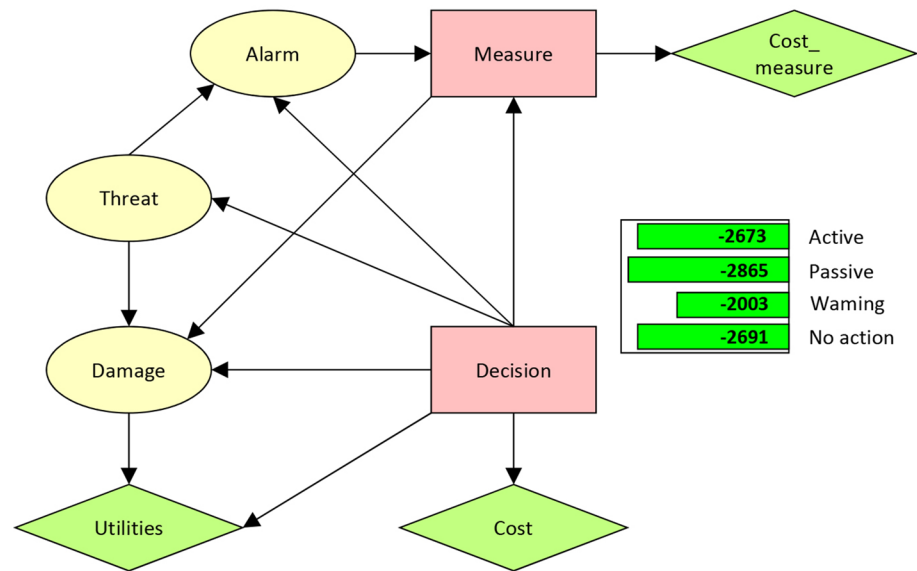
occupation of hills and slopes throughout its history has been promoted. The occurrence of serious geotechnical accidents, particularly of falling blocks, derives from its unique and complex geographic and morphological characteristics. The studies conducted through surface mapping showed a high susceptibility to rock falls [3]. Sometimes there have been observed tears in the slopes during dry periods, and interpretative models originated in thermal actions were proposed [94]. Several containment works have been carried out, as buttresses. Geo-Rio Foundation was created, after severe rainy events that occurred in the city in 1966. Since then, the technical staff formed by engineers and geologists conducts surveys and defines the necessary works to ensure the safety of the population. Geo-Rio has implemented the Rio Alert system, which maintains pluviometry stations scattered throughout the city to monitor the rains. Meteorological radar images are critical to the detection of 108 storms.

3.2 Experience in Hong Kong

Honk Kong is a region associated with China with a high population density, about 7 million people, in a territory of only 1,100 km^2, and very mountainous. About 75% of the territory has slopes greater than 15° and more than 30% has slopes greater than 30°. An aerial view of the construction in Hong Kong is illustrated in Fig. 8a.

It has a history of tragic slope accidents. After 1947, more than 470 people died because of ruptures associated with embankments and retaining walls. In June 1972, major devastating landslides occurred in the regions of Sau Mau Ping, in Po Shan Road and in the territory of Kowloon. Even today, after government actions since 1977, about 300 incidents involving ruptures in containment

structures and natural slopes are reported by the Government of the territory each year. Some landslides that occurred in Honk Kong are illustrated in Fig. 8b–e. Many of the accidents are of minor relevance, such as erosion of the slope surfaces. However, a significant proportion consists of major disruptions that can threaten life and property, block roads and disrupt community life [67].

Hong Kong has a tradition of a high standard in the practice of slope engineering in a territory with a very intense, mountainous urban development, with highly altered formations and often with an adequate drainage system. It can somehow be attributed to the establishment of an efficient safety system, developed by the Geotechnical Engineering Office (GEO) established in the territory [18, 46, 48, 60, 67].

The dominant rock formations are granitic and volcanic, being greatly altered by weathering and, consequently, very heterogeneous. Intrusions on the form of dikes are quite common. Kaolinitic veins are present and may constitute discontinuity filling material. In many embankments, colluvial formations exist because of erosion phenomena [46].

Each year GEO reports hundreds of slope instabilities, the data of which are stored on a database, the vast majority of which are relatively small although larger landslides, with more than 5,000 m^3, occur. A long-term program called LPM (Landslide Preventive Measures) was also introduced to systematically analyze the slopes of government works and carry out a safety analysis of private works. Concomitantly, maintenance programs are established by the various government sectors. It is a fundamental activity to obtain lessons from both built slopes and small-scale and large-scale landslides. Defining risk reduction strategies is one of the most relevant

Fig. 8 **a** Aerial view of Hong Kong; **b–e** some landslides occurred at Hong Kong region (adapted from [83, 84])
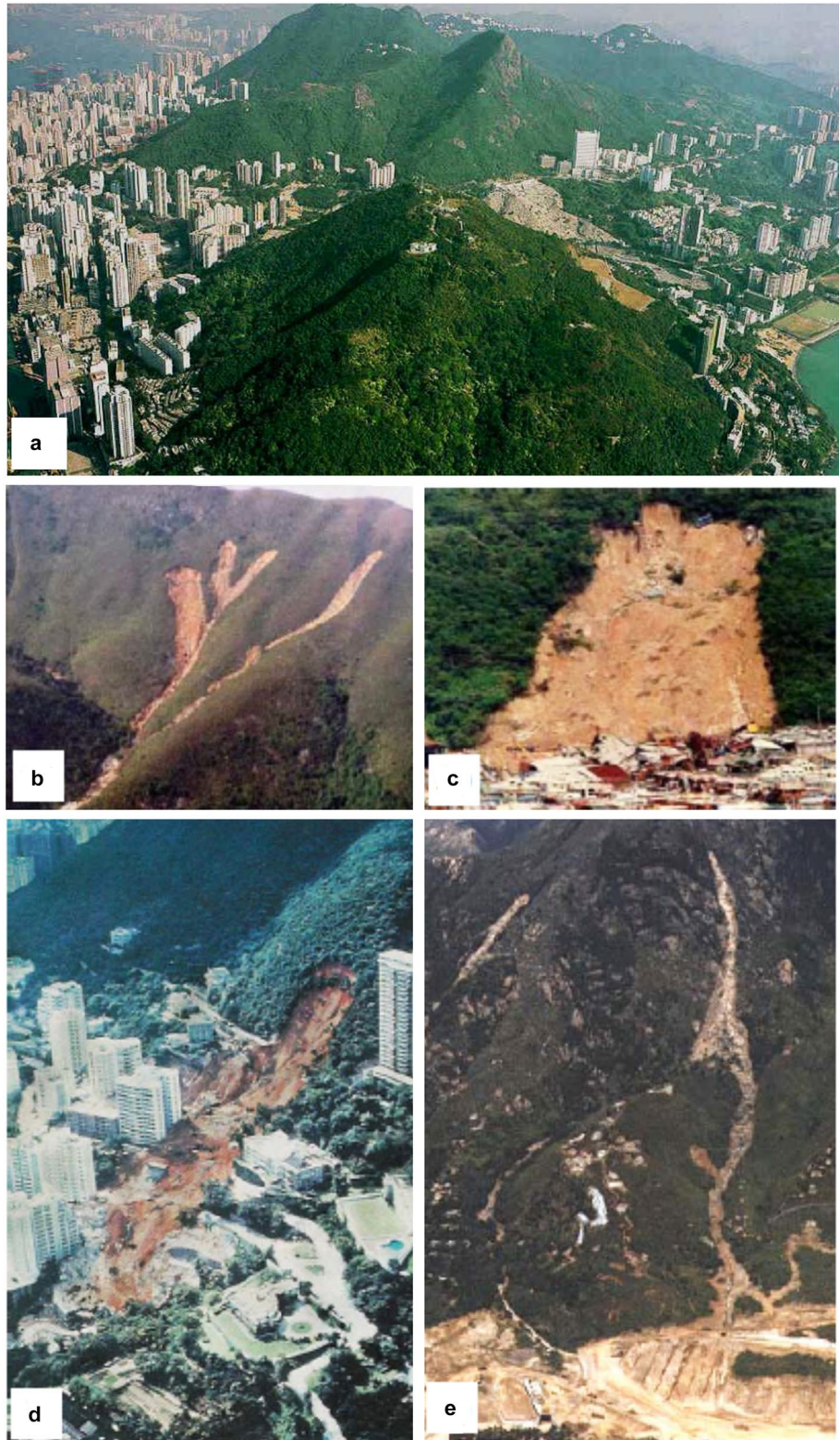
activities being developed to prevent or eliminate certain accidents and includes stabilization, mitigation works, that is to reduce vulnerability, and the establishment of warning notices [47, 67].

Special reference to a study carried out by Hoek [48] for the Sau Mau Ping road, which has a very steep slope on one side of the road and a series of elevated apartments on the other side. It was intended to know what the safety

factor of the slope for normal and exceptional conditions, which can occur during an earthquake or associated with heavy rains during a typhoon, and which safety factor is considered acceptable in the long run. The rock mass associated with the slope is an unaltered granite with discontinuities. The main discontinuities are parallel to the slope surface, and the spacing between them increases with depth. During the excavation of the embankment, small landslides were induced.

Based on the sensitivity studies carried out, instability in this embankment could occur for a totally saturated embankment and subject to an earthquake. At the time, the following decisions were taken [48]: no evacuation of residents along the road in the vicinity of the embankment, execution of horizontal drainage holes made to reduce under pressures; installation of piezometers to measure pressures during periods of greatest rain; closing of traffic in periods of water table that exceed a certain limit; and conducting an investigation to assess the most effective reinforcement or remediation measures aimed at stabilizing the slope in the long term. In the long term, the existing situation was considered unacceptable and a safety factor of 1.5 was adopted. In the studies carried out, the following alternatives were considered: reduction of the slope height; reducing the angle of the slope face; draining the slope; and reinforcement of the slope. The final option chosen consisted of reducing the angle of the slope to 35° by means of an excavation, the slope being used as a quarry, given the scarcity of aggregates at the time, with no slippages occurring after the execution of the works.

Detailed risk analyses are carried out consistently in the territory, as well as the establishment of guidelines for the study of accidents. A flowchart of the slope stabilization actions is illustrated in Fig. 9. The key publications of Malone [67], Ho [46] and Ho and Ko [47] illustrate the strategies followed in the analysis of risk in the territory.

With GEO, inserted in the CEDD (Civil Engineering and Development Department), with the objective of minimizing the risk of slope instability, the Hong Kong Government achieved a reinforcement of the stability of the territory's slopes and a Security System was created. The activities developed are referred to the publication of Chan [19].

3.3 Foundation Geo-Rio

The city of Rio de Janeiro has promoted the occupation of hills and slopes throughout its history. The occurrence of serious geotechnical accidents, particularly falling blocks, derives from its unique and complex geographical characteristics. The photographs illustrated in Fig. 10a, b give an idea of the complexity of the city. Block fall is
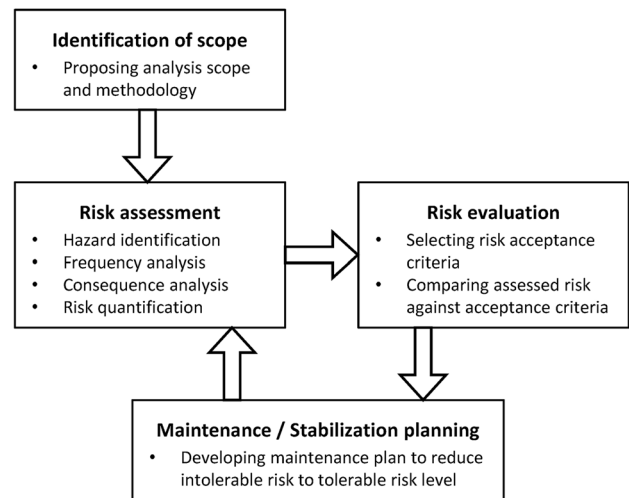
Fig. 9 Flowchart of slope stabilization actions [47]

undoubtedly one of the most complex and most risky problems (Fig. 10c). Studies conducted through the surface mapping showed a high susceptibility to falling chips and blocks evidenced by sections in rock balance, subject to traction efforts [3, 79]. Sometimes breaks in the slopes have been observed in dry periods and interpretive models have been proposed with origin in thermal actions [94]. Several containment works have been carried out, such as buttresses. Figure 10d shows a containment at Morro do Queimado.

The hazards aspects of Hong Kong are very similar to those of the State of Rio de Janeiro and in particular the city of Rio de Janeiro, and Rio has periods of very intense rain.

An Institute of the Municipal Works Department of Rio de Janeiro was founded almost 45 years ago and now called GeoRio Foundation. Its creation occurred after serious rainy events that took place in Rio de Janeiro in 1966. Since then, a technical staff formed by engineers and geologists has carried out surveys and defined the works necessary to ensure the safety of the population. GeoRio implemented the Alert Rio system, which maintains 32 pluviometry stations throughout the city to monitor rainfall. From the analysis of meteorological conditions, the system issues alerts in cases of possible slipping. These alerts are disseminated to the population through the press and the responsible municipal bodies, with removal of families from the places and implementation of other preventive actions [38]. This Institute is also responsible for surveying and registering the geological and geotechnical characteristics of soils, rocks and deposits of construction materials and for the licensing and inspection of projects for the containment of slopes and the exploitation of

Fig. 10 **a** View of Rio de Janeiro city (Brazil); **b** View of Rio de Janeiro (taken from the inselberg called Pão de Açúcar); **c** Block fall in Vila Izabel, Rio de Janeiro [73], **d** Containment work at Morro do Queimado, Rio de Janeiro [73]

deposits by the private sector. GeoRio is also responsible for licensing buildings in hillside areas. It is important to highlight the fact that this Foundation developed the technical manual for hillsides, in use in various entities, universities and professionals in Brazil, dedicated to the analysis and research of slopes, drainage and surface protection, reinforcement of walls with geosynthetics, and anchors and clamps [83, 84].

Geotechnical risk management was started in 1984, covering the most dangerous slopes. It was later extended to the entire city. As mentioned, from 1996 onward, GeoRio implemented the Alert-Rio system that allows to monitor the rainfall in the various stations in real time. The implementation of the Alert-Rio system has been a success, having already issued alert bulletins on several occasions of great rainfall [23, 38, 63]. In projects such as

Rio Vigilante and Infocrise, GeoRio introduced new technologies for the management of landslide risk. The City Council has installed physical boundaries in areas at risk. Figure 11 shows the flowchart of the basic activities that are part of the Rio Vigilante Project from the implementation of the boundaries [38].

Special highlight for the inauguration of the Rio Operations Center in Cidade Nova. The Rio Operations Center monitors the city daily life 24 h a day. All stages of crisis management are integrated, from anticipation, reduction and preparation, to the immediate response to events, such as heavy rains, landslides and traffic accidents. The Center permanently monitors the city and is always ready to act in emergency situations. With an integrated data system and its numerous cameras, it is the headquarters where all actions are coordinated and planned in times

Fig. 11 Rio Vigilante project program (Adapted from [38])
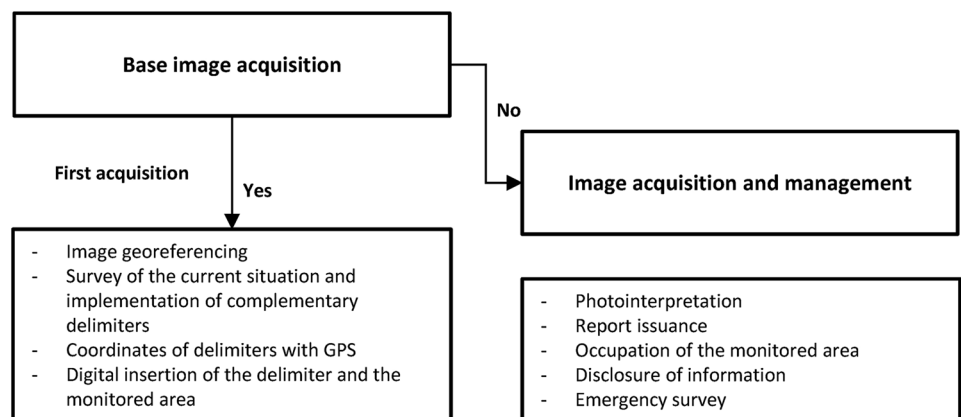
of crisis. All data are interconnected for viewing, monitoring and analysis in the Control Room. In this crisis room, equipped with videoconference, it is possible to communicate with the Mayor's official residence and with the Civil Defense headquarters. The process allows to act in real time in making decisions and solving problems.

Weather radar images are critical for storm detection. This radar takes images and updates them every two minutes and allows observing the location, displacement and intensity of precipitation (rain, hail). The reflectivity captured by the radar can be related to the intensity of precipitation.

The city of Rio de Janeiro has geographical and topographic characteristics, as well as atmospheric patterns, which allow the development of meteorological phenomena that cause significant rainfall (the average annual precipitation is about 2,000 mm), see details in Erassi et al. [35].

The summer months are very rainy, with about 60% of slope slopes occurring during these months. Thus, a database on slopes was created using a GIS system and DM techniques were applied to discover patterns. The tasks associated with data preparation are very important and time-consuming [86–88].

Figure 12 illustrates a map with the rain gauge network of the city of Rio de Janeiro with the 30 rain gauges centered on Thiessen polygons. Data preparation was one of the most important tasks in the DM strategy. Rain rates associated with each slope according to geographical proximity and its occurrence were considered. However, the data showed missing values and were filled out based on the application of ANN (Artificial Neural Networks) techniques [87, 88].

4 Instabilities of Slopes in Rio de Janeiro State

4.1 General

The natural disaster that occurred in the mountainous region of Rio de Janeiro State, on January 11 and 12, 2011, when heavy rains caused floods and landslides in seven municipalities, was considered the largest climatic and geotechnical catastrophe of Brazil [13]. Identified by the United Nations the eighth largest landslide in the world in the last 100 years, the disaster was compared, for its size and damage, to other major catastrophes, such as the one that devastated the Blumenau-Itajaí region, in Santa Catarina in 2008 and that was caused by Hurricane Katrina, which destroyed the city of New Orleans, USA, in 2005 [13]. Many persons died in the natural disaster in the State of Rio de Janeiro, particularly in the mountainous region of the

Fig. 12 Map of Rio de Janeiro and the rain gauge network (adapted from [89])

1 - Vidigal
2 - Urca
3 - São Conrado
4 - Tijuca
5 - Santa Tereza
6 - Copacabana
7 - Grajaú
8 - Ilha do Governador
9 - Penha
10 - Madureira

11 - Irajá
12 - Bangu
13 - Piedade
14 - Tanque
15 - Saúde
16 - Jardim Botânico
17 - Itanhangá
18 - Cidade de Deus
19 - Rio Centro
20 - Guaratiba

21 - Gericinó
22 - Santa Cruz
23 - Cachambi
24 - Anchieta
25 - Grota Funda
26 - Campo Grande
27 - Sepetiba
28 - Sumaré
29 - Mendanha
30 - Itaúna

State (Fig. 13). The mega-disaster reached seven cities mainly Nova Friburgo, Teresópolis and Petrópolis, and it was considered one of the larger events of generalized mass movements in Brazil [83, 84]. According to the documents of the time, doubts arose about what caused the disaster in the proportions that occurred, particularly on the factors that led to so many human losses. The region has always been characterized by a great natural vulnerability, located in the *Serra do Mar*, formed by rocks with thin layer of land and covered by Atlantic forest, with high slope and heavy rainfall regime in summer, characteristics that generate soils more unstable and prone to landslides [11].

The region had not yet experienced a situation of this severity, and entire neighborhoods were covered in a matter of seconds. An emergency and public calamity situation was declared, and a large support network was formed, made up of local, state, and federal public agencies, private organizations, and volunteers. According to the documents of the time, doubts were raised about what caused the disaster in the proportions that occurred and about the factors that led to so many human losses, with high declivity and intense rain regime in the summer, characteristics that generate more unstable and prone soils to landslides.

A simplified geological map of the mountainous region of the State of Rio de Janeiro is shown in Fig. 14.

4.2 Nova Friburgo

The mega-disaster in the mountainous region of Rio de Janeiro left an incalculable number of landslide scars on the slopes of four municipalities (Nova Friburgo, Teresópolis, Petrópolis and Sumidouro), but mainly in Nova Friburgo, a high number of deaths and displaced persons, being the biggest disaster in Brazil caused by natural disasters [6, 25, 74].

The Geological Survey of the State of Rio de Janeiro, through its Center for Analysis and Diagnosis of Landslides, carried out emergency care to support the response and rehabilitation to the mega disaster, and, since then, developed, in partnership with Universities in the State of Rio de Janeiro, in the analysis of the conditions of disastrous landslides. This study does not attempt to be exhaustive in the analysis of the tragic accident that occurred in Nova Friburgo. The excellent work developed by DRM-RJ (Department of Mineral Resources of Rio de Janeiro State) [26, 27]

Figure 15 shows several significant landslides associated with the slopes of the municipality of Nova Friburgo, which illustrate well the severity of the accidents that occurred.

Another important accident occurred at Três Irmãos as referred to Fig. 16 occurred in November 2012 [27]. It was a particularly rainy month, characterized by very heavy rain showers or significant accumulated rain over 24 h. Heavy rains were recorded on days 5 and 6, as shown in Table 2. The previous days were of low rainfall, which explained the fact that there were no accidents. The Três Irmãos accident occurred on the afternoon of the 13th, with a large rocky block of 4,000 m³ standing out, due to planar landslide caused by water percolation, on the rupture surface filled with altered material with a maximum thickness of 20 cm. According to the DRM-RJ

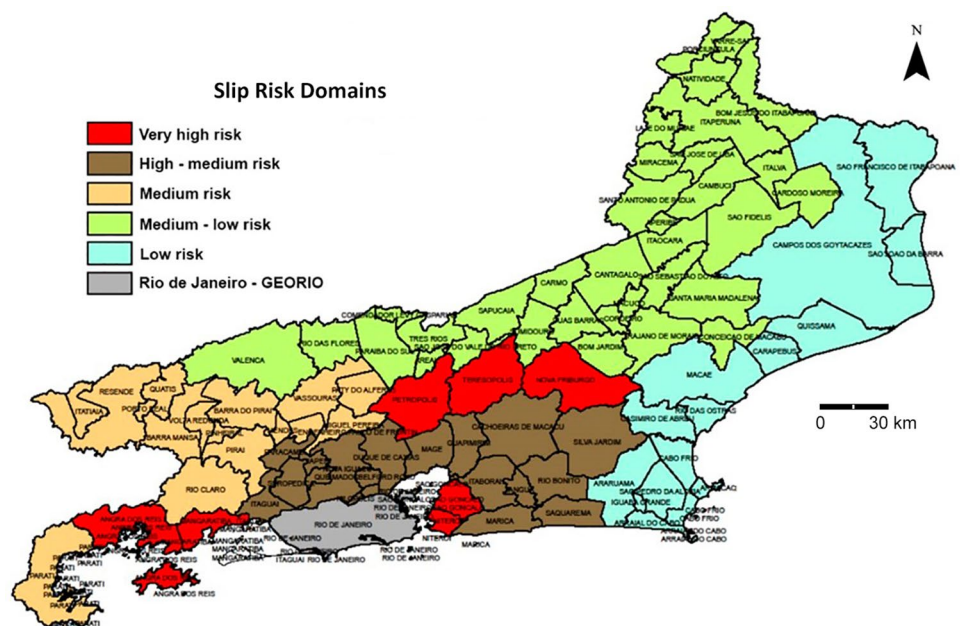**Fig. 13** Rio de Janeiro State. Diagnosis of risk of landslides

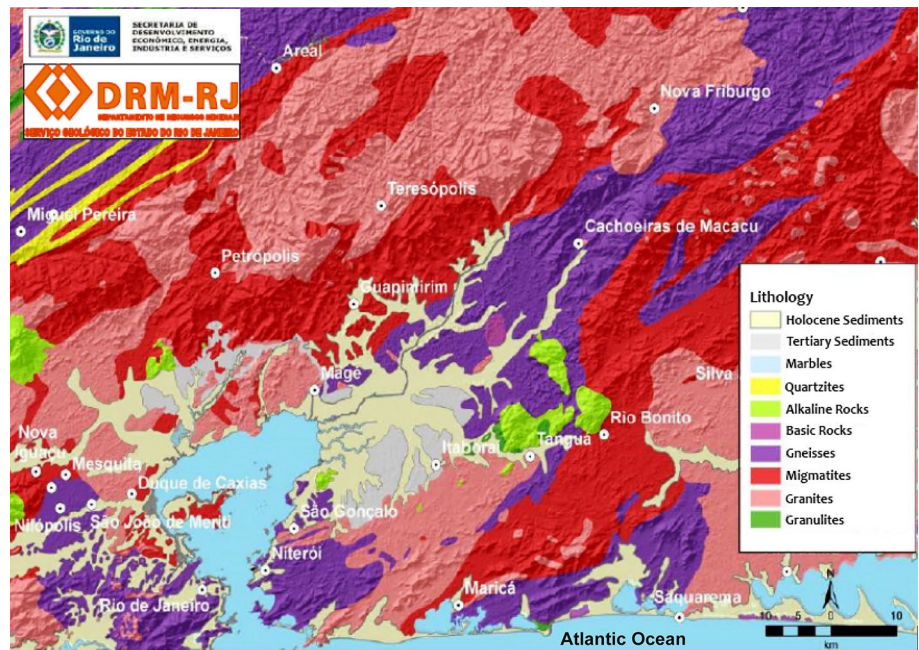**Fig. 14** Simplified geology in the State of Rio de Janeiro

Fig. 15 **a** Rock blocks at the base resulting from a landslide; **b** Nova Suíça. Planar landslide with material deposition; **c** building destroyed by a landslide; **d** building partially destroyed by a landslide

report, the accident started at 5:30 am with a block drop associated with 19 mm/h. Two hours later, a 21.6 mm/h rain shower occurred, with the movement of the large block of rock being at 4 pm, when the rain had practically stopped. The slip seems to have occurred through a relief joint and in combination with traction fractures present in the highest part of the escarpment.

It should be noted that risk scenarios for landslides were built from the analysis of the correlation between intense rains, having been developed since December 2011, and which allowed the operation of the alert and

Fig. 16 Três Irmãos land-slide accident [27]
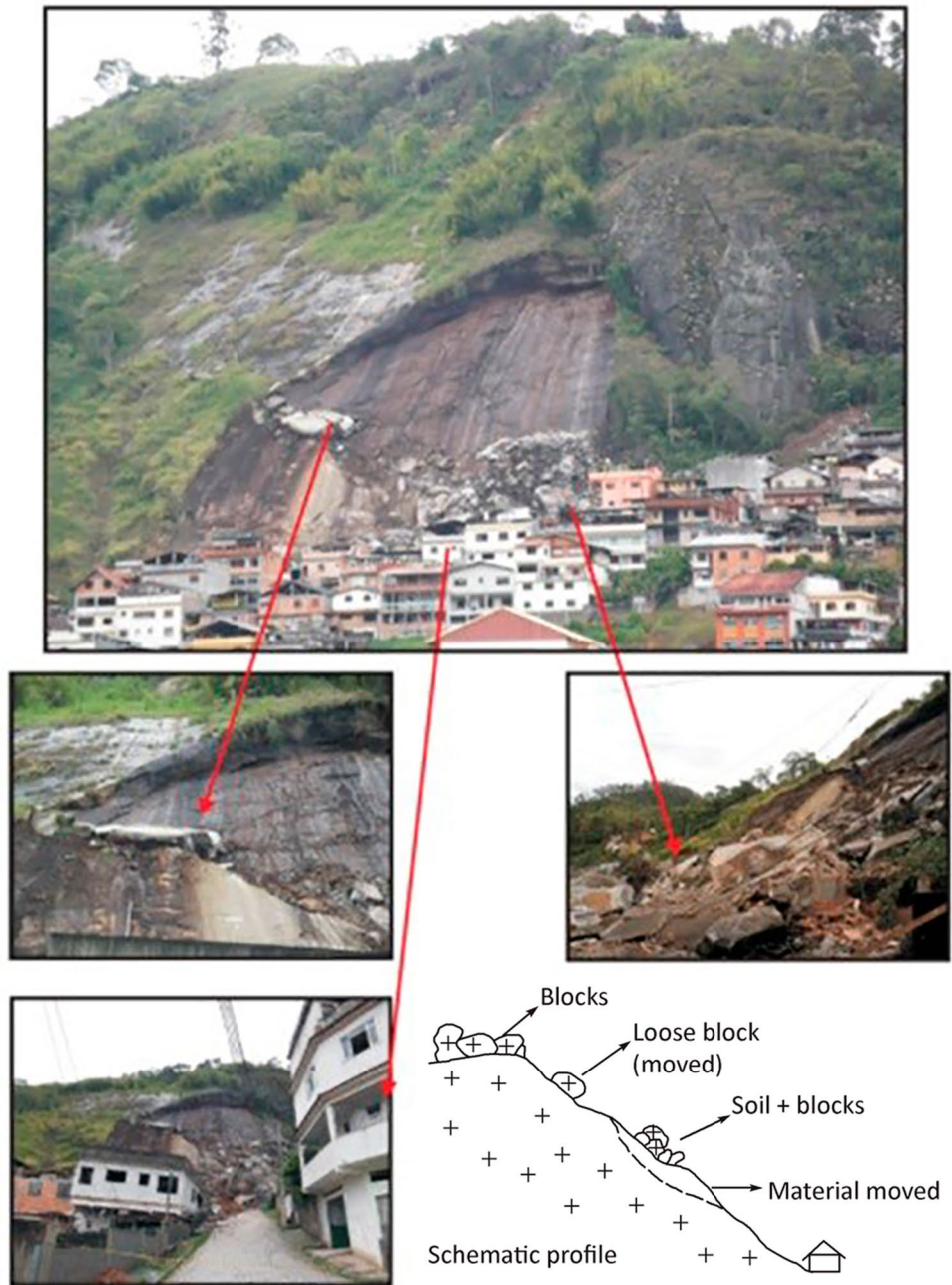
Table 2 Rain data on November 5 and 6, 2012 [27]

Location	Peak	Rainfall	Background
Macaé (Glicéroo–INEA)	05–15 h	44.80 mm/h	3.6 mm/24 h; 16.4 mm/96 h; 60.6 mm/month
Silva Jardim (INEA)	05–16.45 h	25.48 mm/h	13.0 mm/24 h; 33.8 mm/96 h; 61.2 mm/month
Petro (Posse–INEA)	06–01.45 h	32.78 mm/h	4.2 mm/24 h; 6.0 mm/96 h; 84.0 mm/month

alarm systems for landslides [26, 27]. Figure 17 shows rainfall curves, the yellow one separating the domain in which no landslides were recorded with the domain associated with sparse landslides; and the red one that separates the domain of sparse landslides with generalized landslides. Based on these curves, the scenarios identified in Table 3 were defined.

Fig. 17 Critical rainfall curves for the mountainous region [27]
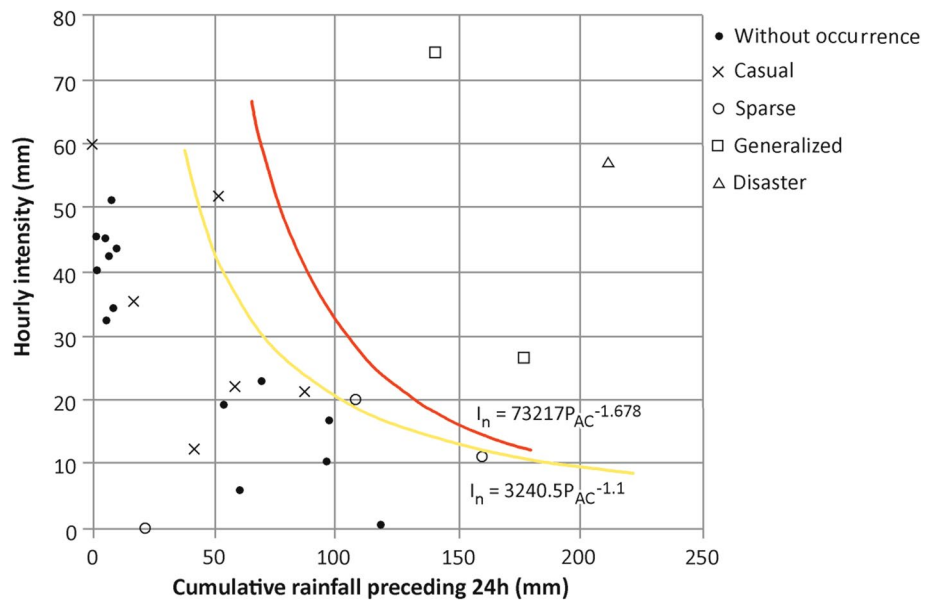
4.3 Other cities

In relation to Petrópolis, a research work was performed on the simulation of the process of falling blocks on slopes in this municipality, with the application of contact mechanics, embodied in the work of Ribeiro [73]. The study was delimited in an area of Bairro da Glória subject to the occurrence of falling blocks. The range of the blocks was analyzed in view of the change in the physical parameters of the geotechnical units that make up the terrain. For this, numerical simulations were carried out using PFC-3D discrete element software [53]. In geological terms, the area is formed by rocky outcrops of hornblende-biotite gneiss, often found covered by residual soil. The Serra dos Órgãos batholith is present in the central and southeast portions of the municipality. The rocks of this unit are intensely deformed and metamorphized and are often migmatized and fractured. There are three families of discontinuities present in the rock mass, which intersect, creating conditions for the occurrence of falling blocks. These discontinuities vary widely in the diving angle, ranging from vertical to horizontal [73].

Figures 18 and 12 show blocks that were selected for simulations with the discrete block method as shown on the mountain [73]. The terrain topography generated by the PFC-3D software is shown in detail in Figs. 19, 20 and 21 which represent, respectively, the trajectories of the spherical, octahedral and real geometry blocks according to the conditions of stiffness and damping explained by Ribeiro [73].

Table 3 Risk scenarios assigned by DRM-RJ (Department of Mineral Resources of Rio de Janeiro State) adapted from [26, 27]

Scenario	Type of accident	Hourly rainfall	Daily rainfall and others	Comments
Occasional landslides	<5 per municipality	<30 mm/h	<100 mm/day	Occasional accidents
Sparse landslides	5 < n < 25 per municipality	>30 mm/h	>100 mm/day > 115 mm/96 h > 300 mm/month	Sparse accidents; yellow curve; n—no. accidents; affect slopes and drainage lines
Widespread landslides	>25 per municipality	>50 mm/h	>120 mm/day > 130 mm/96 h > 300 mm/month	Accidents with mobilization of sliding masses; large and flowing landslides
Disasters associated with landslides	>50 per municipality	–	–	Great no. of natural and induced accidents; large mass movements; large record of prolonged rainfall events
Great catastrophes	Number not yet reached in disasters	80 mm/h	>250 mm/day > 400 mm/96 h > 600 mm/month	Related to a number not yet faced with natural disasters and induced

Fig. 18 View of 12 blocks selected for simulations with the discrete block method [73]
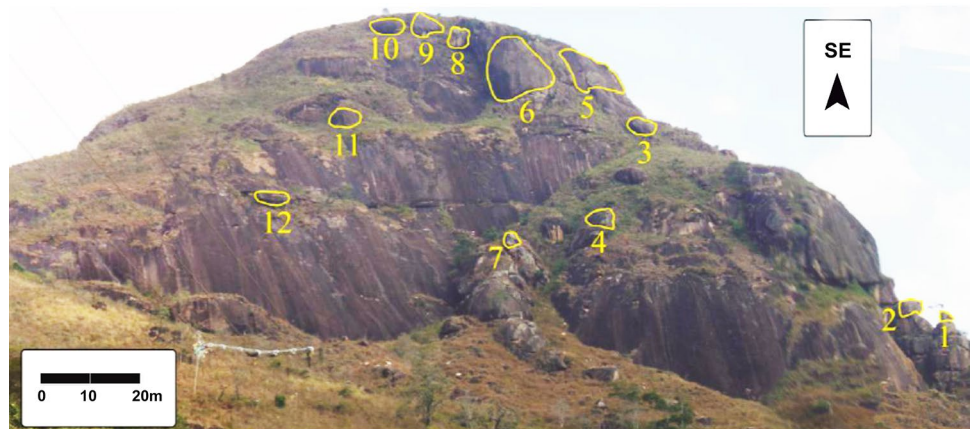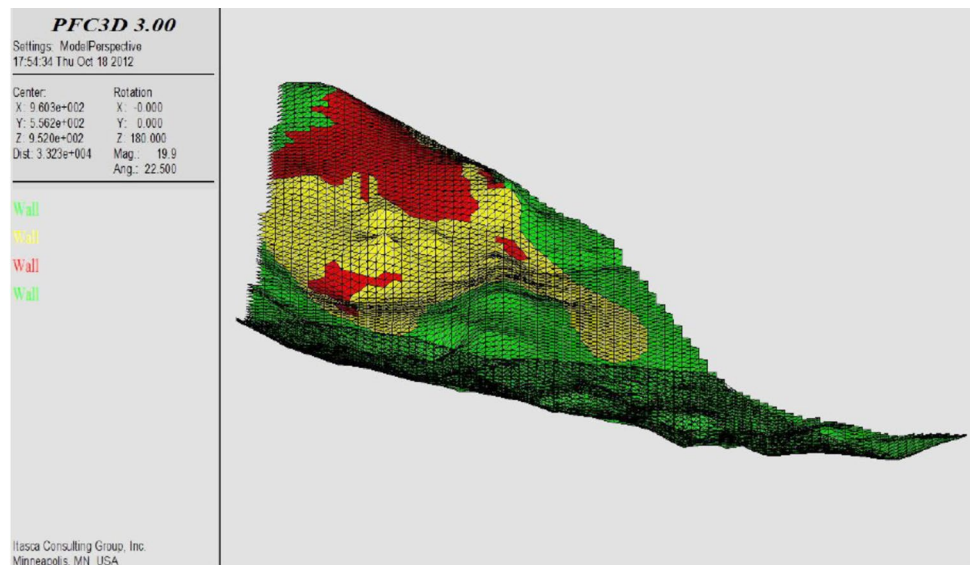

Fig. 19 Land topography generated by the PFC-3D [73]. Land topography generated by the PFC-3D [73]

According to the results, it was possible to state that the jump is the predominant mode of movement for the spherical blocks and the rolling occurs in the final portion of the course. For octahedral blocks, there are different modes of movement involved along the route. In certain trajectories, the blocks slide. In others, jumping and rolling seem to be present. However, the heels of octahedral blocks have smaller dimensions when compared to the jumps of spherical blocks. In blocks with approximate real geometries, there is a predominance of sliding as a mode of movement. And this is exactly the expected behavior for chips and blocks whose shape does not approach a sphere. Possibly, the different behaviors assumed by the blocks in their trajectories changed the way in which the rigidity and damping interfered in the reach of the blocks.

In the case of the Municipality of Teresópolis, located in the central stretch of the State of Rio de Janeiro, the region is characterized by deposits of gneiss and granite, dating from the Precambrian period, and by a very accentuated relief, where the predominant physiography is represented steep cliffs [71]. Image of landslide in this municipality is illustrated in Fig. 22. After the mega-disaster, in January 2011, as well as the heavy rains that affected the municipality in April 2012, caused most of the problems socioenvironmental and lack of environmental management. From the field surveys, it can be inferred that the basic characteristic of the soil on the slopes of the municipality is of little depth and prominent rock outcrop; that is, in the areas of slopes, the soil has a horizon of little depth above granite rock formation. Such aspects, allied to the presence of rocky outcrops in the process of weathering, as well as occurrences rainfall and steep slopes were some of the factors that have contributed and have contributed to landslides occurred in Teresópolis.
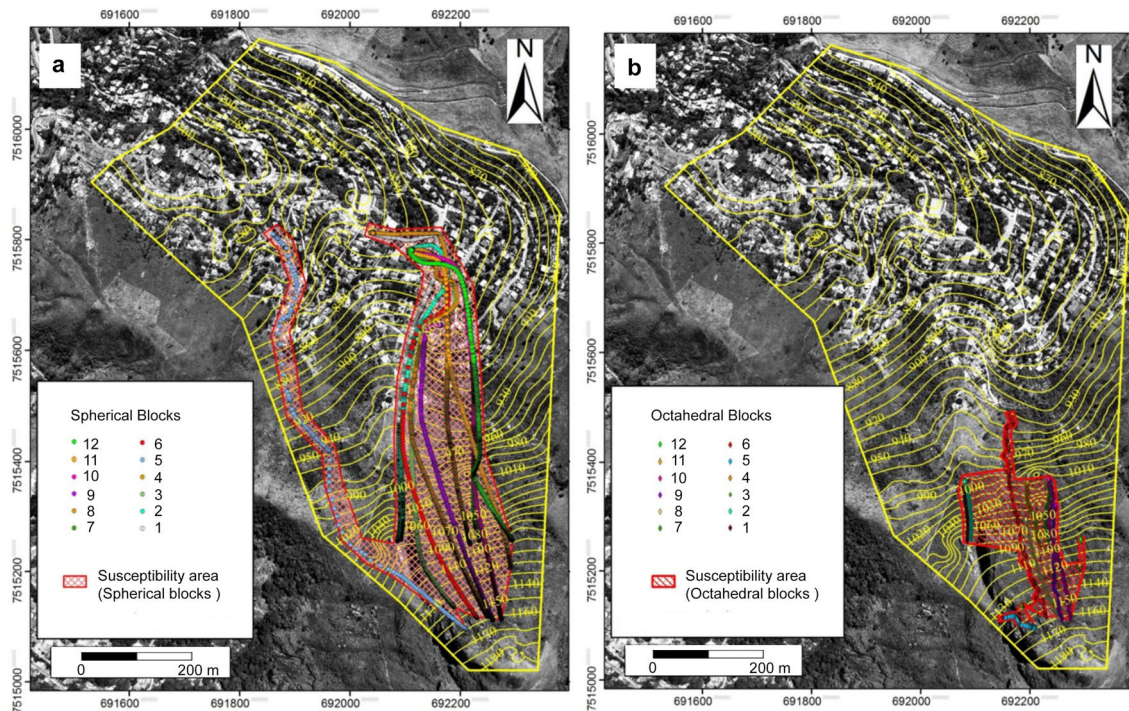
Fig. 20 **a** Trajectories and area susceptible to falling spherical blocks [73], **b** Trajectories and area susceptible to falling octahedral blocks [73]

Fig. 21 Trajectories and area susceptible to falling of blocks with approximate real geometries [73]

5 Conclusions

The study focused on the role of water in the evaluation of landslide hazards. Landslide hazards include uncertainties in a deterministic and probabilistic form, and model uncertainty in hydrologic models can be related to models that solve the flow in soil formations, nonsaturated and saturated media, or in fissured rock masses. Model uncertainty in stability modeling comes from the stability models themselves, but in combined models the uncertainty comes from both models. The study discusses in detail different approaches for risk assessment and levels followed in the decision approaches.

The management of landslides is discussed, being emphasized the situations that occurred in Hong Kong territory, as well as in Rio de Janeiro city. In the case of Hong Kong, a mountainous terrain exists, with heavy rain and dense development which make the region prone to risk from landslides. To reduce this risk, a comprehensive slope safety system was implemented through the setting up of safety standards, and administrative geotechnical controls, as well as the upgrading and maintenance of slopes. The overall risk reduction achieved was a result of the effectiveness of the implemented system. A long-term program called Landslide Preventive Measures was introduced to systematically analyze the slopes of government works and carry out a safety analysis of
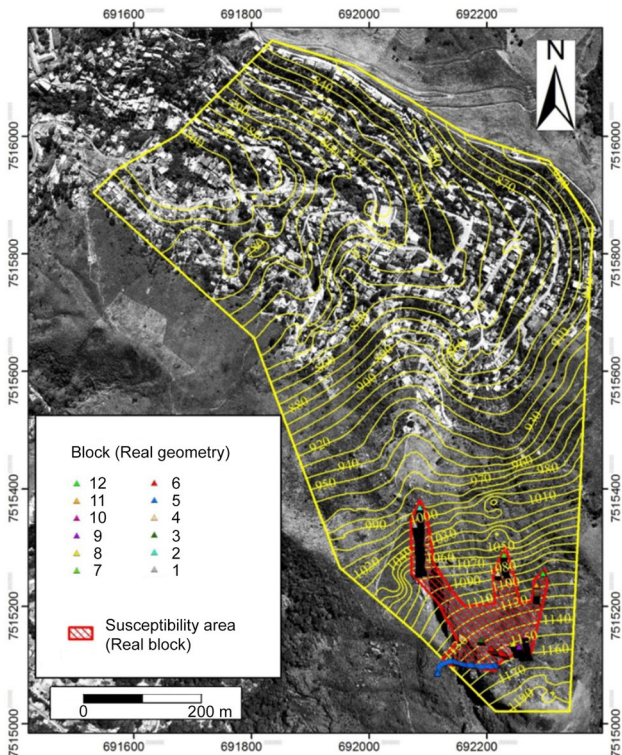
Fig. 22 Landslides in Teresópo-lis [25]

private works. Concomitantly, maintenance programs were established by the various government sectors.

Specific aspects of slope instability in the Rio de Janeiro city were also analyzed in detail. The city had promoted the occupation of hills and slopes throughout its history. The occurrence of serious hazards happened, with incidence in falling blocks, derived from its unique and complex characteristics. The municipality of Rio de Janeiro founded the so-called Geo-Rio Foundation to define the works necessary to ensure the safety of the population. Geo-Rio implemented the Alert Rio system, which maintains pluviometry stations throughout the city to monitor rainfall. From the analysis of meteorological conditions, the system issues alert in cases of possible landslides. This foundation is also responsible for surveying and registering the geological and geotechnical characteristics of soils, rocks, and deposits of construction materials and for the licensing and inspection of projects for the containment of slopes and the exploitation of deposits by the private sector.

Finally, as a case study, the mega-disaster of the mountainous region of the State Rio de Janeiro due to heavy rainfall is studied. It occurred between January 11 and 12, 2011, and later in 2012, reaching seven cities, mainly Nova Friburgo, Teresópolis and Petrópolis, and it was considered one of the larger events of generalized mass movements in Brazil. The region has always been characterized by a great natural vulnerability, located in the *Serra do Mar*, formed by rocks with thin layer of land and covered by Atlantic forest, with high slope and heavy rainfall regime in summer, characteristics that generate soils more unstable and prone to landslides.

Authors' contributions Luis Ribeiro e Sousa designed the study. Luis Ribeiro e Sousa, Eurípedes Vargas Jr., Rita Leal Sousa and Karim Karam supported the data acquisition, analysis and modeling. Helder I. Chaminé gave inputs on the structural geology, engineering geosciences and hydrogeology of the study sites. All authors contributed to the data analysis, interpretation and discussed results. Luis Ribeiro e Sousa and Rita Leal Sousa wrote the manuscript with contributions of all authors. Luis Ribeiro e Sousa and Helder I. Chaminé performed the revision of the final edited version.

Compliance with ethical standards

Conflict of interest No potential conflict of interest was reported by the authors.

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