Landslide hazards in Santiago, Chile: An overview

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Abstract: Santiago, the capital city of Chile, is the country's largest city, with a population of over 5 million people. It is located in a depression between the Coastal Range and the Andes Main Range. The city is placed on fluvial and alluvial sediments and varies in altitude between 500 and ca. 1,000 m a.s.l. The eastern fringe of the urban area is directly situated next to a steep, rocky mountain chain as high as 3,250 m a.s.l. Several ravines drain this range towards the city, their alluvial fans being increasingly occupied by new housing estates.

During heavy rainfall, it is common for landslides to be triggered on the steep slopes of the mountain. Particularly important are debris and mud flows, the runouts of which reach the alluvial fans in the city margin, posing an important hazard. The most catastrophic event of this type took place on May 3rd 1993, when several debris flows affected the city, causing about 30 fatalities and significant material losses, with over a thousand houses partially or totally damaged. Other landslides that may locally affect houses built on the hills and other infrastructure are rock falls and rock slides. Due to the important seismic activity in the region, landslides can also be triggered by earthquakes.

A complete landslide hazard assessment of the eastern area of Santiago is being conducted in order to generate a useful tool for urban planning and risk analyses. The studies include estimation of triggering factor thresholds, geotechnical characterisation of rock and soil in the unstable areas, the development of a hazard assessment methodology adapted for the regional conditions and an evaluation and zoning of the hazard posed by the different landslide types in the area.

Résumé: Santiago c'est la ville la plus importante du Chili, avec une population supérieure à 5 millions des personnes. La ville est située dans une dépression centrale entre la Cordillère de la Côte et la Cordillère Principale des Andes, sur des dépôts fluviatiles et alluviaux et à des altitudes entre 500 et 1000 m s.n.m. Une chaîne de montagne avec des altitudes jusqu'à 3250 m s.n.m. est située donc à la limite est de cette ville. A la base de cette chaîne des nombreux cônes alluviaux actifs sont de plus en plus urbanisés par des projets immobiliers. Sporadiquement, des glissements de terre et des flux alluviaux, générés par des pluies intenses, peuvent affecter la surface des ces cônes et constituent une source importante de danger pour la population. Le plus important de ce type de événement au cours des dernières années c'été le 3 Mai 1993, quand une série des flux alluviaux et des glissements de terre ont causé la mort de 30 personnes et ont produit des pertes matérielles importantes, comme la destruction des milles des maisons. En plus, des avalanches des pierres et des tombées des blocks peuvent affecter aussi localement la population et des bâtiments. Autre, les glissements de terre peuvent aussi être générés par des séismes, très courant dans cette région des Andes. Une étude d'évaluation des risques géologiques en concernant la zone est de la ville est en cours, avec l'objectif de constituer un outils pour lévaluation du danger potentiel et la projection des zones urbanisables en sécurité. Cette étude prend en compte les facteurs détonant des processus, la caractérisation géotechnique du sol et du substratum des zones instables, le développement d'une méthodologie pour l'évaluation des zones des risques géologiques adaptée à des conditions régionales et une cartographie des différent types des glissements de terre et des avalanches de pierres dans la zone.

Keywords: Geological hazards, landslides, slope stability, geology of cities.

INTRODUCTION

Chile, located in the southern Pacific coast of South America, in the convergent margin of the Nazca and South America plates. This tectonic setting produces seismic activity and mountain building, forming the Andes. The related geomorphology induces heavy rains by orographic control and slope instability. Therefore, the country is periodically affected by natural hazards, such as strong earthquakes, floods and landslides.

The capital city of Santiago is located in Central Chile, in the foothills of the Andes Main Cordillera. It has a population of over five million people. The city is placed on fluvial and alluvial sediments and varies in altitude between 500 and ca. 1,000 m a.s.l. Santiago is usually affected by flooding, mainly associated to a deficient drainage system, and strong earthquakes, the last (M 7.8) in 1985 that caused severe damage and over a hundred fatalities. In the last decades, the city has suffered a quick expansion with insufficient planning. Part of this growing has been into the mountain foothills, which geology and historical records show to be commonly affected by landslides. These new urban emplacements have increased the risk associated with landslide hazards, with an important manifestation in May 3, 1993, when a number of debris flows invaded several neighbourhoods causing a significant disaster.

This paper reviews the engineering geological characteristics of Santiago and the landslide activity around it, and introduces current research aimed at developing landslide hazard assessment techniques that will allow improving the territorial planning in Santiago and other cities in the country of similar geographical situation.

ENGINEERING GEOLOGY OF THE SANTIAGO REGION

Geology of Santiago

Santiago is located between 33º and 34ºS, about 100 km east of the coast. The city is built in the Central or Intermediate Depression, which is a basin refilled mainly by alluvial and fluvial sediments and, in a smaller proportion, by material associated to volcanic activity. The Central Depression constitutes a north-south trending morphostructural unit located between the Coastal Cordillera, to the west, and the Andes Main Cordillera, to the east (Figure 1). This configuration would have been generated during a maximum compression phase during Upper Oligocene – Middle Pliocene (Thiele, 1980), related to the subduction tectonic regime that has dominated the region since the Jurassic (Thomas 1958). The origin of this basin has been considered tectonic, delimited by north-south trending faults, particularly to the east (Brüggen 1950, Borde 1966). Recent studies of this structure, denominated the San Ramon Fault, indicate that it corresponds to a reverse fault (Rauld 2002). The basement of the Santiago basin would correspond to volcanic rocks (Abanico Formation) assigned to Upper Oligocene – Lower Miocene (Charrier & Munizaga, 1979). Gravimetric studies (Araneda, Avendaño & Merlo 2000) show that the bottom of the basin is a very irregular surface, with buried hill chains, of over 500 m depth in some locations. Part of those chains outcrop in the basin, such as San Cristóbal, Chena, Lonquén and Santa Lucía hills. The basin sedimentary infill has been assessed by drillings only to around a depth of 120 m. The sediments correspond mainly to alluvio-fluvial sediments originated in the river basins of the Maipo and Mapocho rivers, fluvial sediments contributed by Lampa, Colina (Figure 2) and Angostura creeks, and volcanic ash deposits, deposited during an important volcanic eruption dated to 450,000 years B.P.

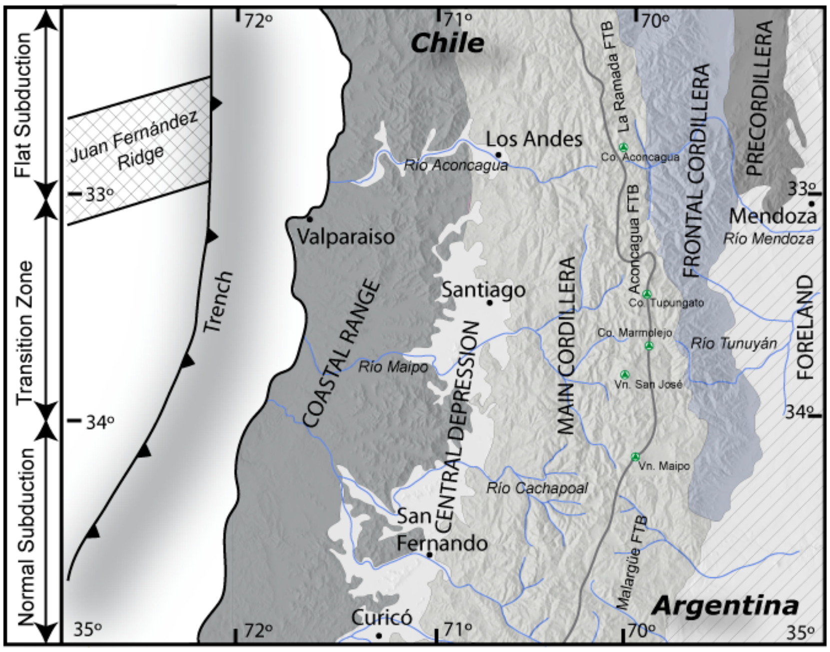

Figure 1. Morphostructural segmentation of Chile between 32º S and 35ºS (after Fock, 2005).

Near the eastern boundary of the Santiago basin the fluvial sediments grade laterally into alluvial fan deposits from ravines originated in the San Ramón Range, a mountain chain which constitute the foothills of the Main Cordillera (Figure 2). This north-south trending mountain range delimits the basin between both the Mapocho and Maipo rivers, with a length of about 25 km. The peak altitude of this range is 3,253 m a.s.l., more than 2,000 m above the city. Several ravines drain the range towards the city, with average gradients exceeding 15º and tributary gullies that may have gradients exceeding 30º. The main ravines of this system are San Ramón and Macul, with drainage basins of 38 and 23 km^2, respectively (Figure 2). Other important ravines are Apoquindo, Nido de Aguilas and Lo Cañas. The San Ramón Range is composed of stratified volcanic and sedimentary rocks of the Abanico Formation (Thiele 1980). The unit is faulted and folded, in the upper part of the mountains showing subvertical dips and moderate to strong jointing, whereas lower down it dips gently to the east. The subvertical bedding creates a structurally controlled network of small gullies that form a very efficient drainage system (Naranjo & Varela 1996). The steep slopes (20º to > 40º) combined with jointing and weathering processes generate important colluvial deposits formed by loose rock blocks and boulders in a matrix of sand and fines (Figure 3), as well as old landslide deposits of similar composition. North of Mapocho river outcrop similar rocks of Abanico Formation with intrusive bodies

The basin is closed to the south by a low altitude hill chain composed by rocks of Abanico Formation and Cretaceous volcanosedimentary rocks of Las Chilcas Formation (Fock 2005). This and other volcanic and volcanosedimentary formations, as well as intrusive bodies from the Cretaceous conform the western and northern edge of the basin, forming the foothills of the Coastal Cordillera (Wall, Sellés & Gana 1999). The western part of the basin is dominated by ignimbritic deposits (Pudahuel Ignimbrite), a 40 m deep sequence of pyroclastic ash flow and surge deposits, described by Rebolledo *et al.* (2006, this volume). The basin is limited to the north by small Miocene intrusive bodies of dioritic and andesitic composition.

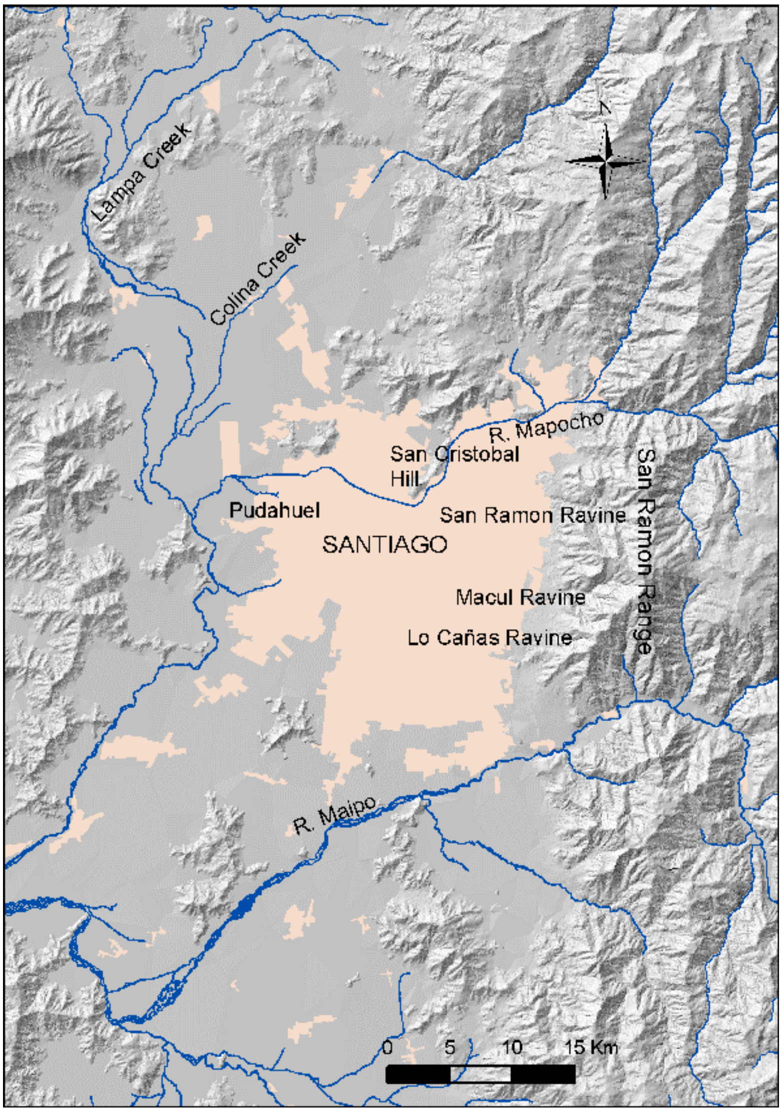

Figure 2. Digital elevation model of Santiago basin, indicating the main geomorphological features named in the text.

Figure 3. Deposit of loose rock blocks and boulders in a sandy matrix in an area of confluence of several small streams and gullies, in the upper part of the San Ramón drainage basin, at about 1,450 m a.s.l. These kinds of deposits, common in the ravines of eastern Santiago, are remobilized as debris flows during heavy rain events.

Geotechnical characteristics of soils and rocks

The Central Depression at the latitude of Santiago comprises four soil units of alluvial, fluvial and volcanic origin with different geotechnical characteristics. The north-western part of the valley is dominated by alluvial silt and high plasticity clay soils deposited by the Lampa and Colina creeks (Valenzuela, 1978). Some of these soil formations exhibit swelling problems and shallow water tables, causing problems for foundation design and flooding hazards. The ash deposits of Pudahuel Ignimbrite that outcrop in most of the western edge of the basin are good foundation soils and may sustain nearly vertical cuts (Valenzuela, 1978). However, their seismic response is not as good, due to low shear modulus values that cause high deformations at low stresses and therefore high levels of seismic wave amplification (Rebolledo *et al.*, 2006, this volume). The city centre and most of the older parts of the city are located on fluvial deposits informally called the Santiago Gravel. This soil is composed by boulders usually less than 20 cm in diameter in a matrix that varies from silty gravel to silty sand, with sandy and clayey lenses. The soil has a high density, low deformability and good geotechnical properties for construction (Valenzuela, 1978). The soil originates in the deposits of the Mapocho and Maipo rivers, grading to coarser deposits closer to the apex of the rivers alluvial fans, to the northeast and southeast, respectively. The eastern part of the valley is mainly dominated by the alluvial fans of the ravines that drain the San Ramón range. These soils are composed by rock blocks in a silty and clayey matrix with varying amounts of sand, deposited by alluvial and hillslope processes, and present heterogeneous geotechnical properties: closer to the mountain foothills, the materials are coarser and more heterogeneous, while in the distal zones they tend to be more stratified and homogeneous in texture and granulometry (Valenzuela, 1978). Similar deposits of smaller extension are located in the foothills of the Coastal Cordillera, in the western edge of the city (Fernández, 2001).

The rocks that form the mountainous relief that surround the Santiago basin have geotechnical characteristics which are mainly related with their lithology and age (Fernández, 2001). The Cretaceous rocks of the Coastal Cordillera, a sequence of volcanic (mainly andesitic) and clastic sedimentary rocks, conform an old relief, with a high degree of weathering and development of clayey residual soils. In contrast, the volcanics of Abanico Formation in the Main Cordillera are of young relief, with steep slopes, fresh rock outcrops and negligible development of residual soils. The rocks are subject to the action of ice and snow in winter, producing intense jointing and generation of coarse debris that infill the basin by active alluvial and fluvial transport systems. Similarly, the intrusive bodies show different properties according to their age, the large Mesozoic batholiths forming smooth relief due to intense weathering and formation of saprolite, while younger Miocene stocks, dikes and sills that intrude mainly in the Main Cordillera show low weathering, high strength and form distinct topographic features.

LANDSLIDES IN THE SANTIAGO AREA

Rain-induced debris flows

Debris flows are the most important type of landslide hazard in Santiago, being triggered in loose sediments in the ravines that drain the San Ramón Range. These materials, the product of chemical and mechanical weathering, are gradually transported by the drainage system and accumulate in ravines and stream confluence areas (Figure 3), where they can be remobilized as debris flows during heavy rain episodes. There are records of flows in 1908, 1936, 1957, 1982, 1986, 1987, 1991, 1993 (García, 2000), 2004 and 2005 (Figure 4). Some of these may be considered as mud flows or hyperconcentrated flows, although in this work they will all be named as debris flows. The most common locations of flows are the Macul and Lo Cañas Ravines, in the southern part of the range (Figure 4).

The most common triggering factor for debris flows and landslides in general in the Santiago region is heavy rainfall. Santiago has a Mediterranean climate; precipitation falls mainly in winter, whereas the summer is dry and warm. The average annual rainfall ranges from 312 mm in the city centre to over 350 mm in the foothills. Heavy rainfalls are more common during El Niño climatic events. El Niño corresponds to the warm phase of the El Niño Southern Oscillation (ENSO) climatic phenomenon. Heavy rainfall events in central Chile, lasting a few days to a week, are associated with convective storms shifting from mid-latitudes toward the subtropical areas, concomitantly with the characteristic weakening of the South Pacific Subtropical Anticyclone during El Niño events (Rutllant & Fuenzalida 1991).

There is a strong positive correlation between El Niño events and the total amount of annual rainfall during the 20th century (Rutllant and Fuenzalida, 1991). These episodes are usually related to flooding, landsliding and the occurrence of debris flows in the area (Sepúlveda, Rebolledo & Vargas 2005).

The May 3, 1993 debris flows caused the largest impact on the city, due to its large volume and the increasing expansion of the city toward the alluvial fans over the last few decades. The main flows occurred in the San Ramón and Macul ravines (Naranjo & Varela, 1996), while some smaller flows in minor ravines such as Lo Cañas were also reported (Sepúlveda & Rebolledo 2000). A frontal system produced heavy rainfall over the Andean Main Cordillera of central Chile, concurrently with warm conditions in the troposphere, during a moderate El Niño event (Garreaud & Rutllant 1996). Although the total daily rainfall in Santiago City was only around 30 mm, the maximum rainfall intensity reached 12 mm/hr at 11:00 hrs, which is a high value expected only every 25 years (Garreaud & Rutllant 1996). Rainfall recorded in the previous evening was less than 10 mm (Naranjo & Varela 1996). Altogether, anomalously warm tropospheric conditions associated with the influence of tropical air masses, produced a rise of the 0ºC isotherm from its average altitude around 2600 m a.s.l. to 4000 m a.s.l., increasing the catchment area for liquid precipitations. The heavy rain on the loose, partially saturated soil deposits in the ravines and slopes, together with an increase of the runoff, saturated and fluidized the soils, forming the debris flows. The same meteorological event produced mudflows, river overflows and flooding in the Main Cordillera east of Santiago (Maipo Valley). The flows of Macul and San Ramón mobilized over $2x10^6$ m^3 of material. The dense and viscous mass transported rock blocks of several metres, as well as trees and vehicles, moving with velocities exceeding 30 km/h and the waves reaching heights of over 10 metres (Naranjo & Varela 1996). The flows reached the city in a few minutes. The overflow of the channels greatly expanded the area affected by the flows, which changed into mudflows in the more distal parts that ran following streets and avenues and flooding the houses with mud and water. According to government accounts, 26 people died and 8 were reported missing. Over 5,000 houses were damaged or flooded by the flows, and 307 were destroyed. Over 28,000 people were affected by the event. A rough estimate accounts for around 5 million dollars in damage and costs to solve the emergency (Sepúlveda *et al.* 2005).

Slides and rock falls

Besides the debris flows, small soil and rock slides and rock falls are common in the valleys and ravines during heavy rain or due to seismic activity (Figure 4). These processes are common in the Main Cordillera, and are more abundant farther into the mountains, particularly in the Mapocho and Maipo valleys, outside the area subject to this study. Around Santiago, small rock falls in the foothills, and some of the hills that outcrop in the basin, such as San Cristóbal hill, are recorded sporadically. For instance, in 2002 a rock fall event was registered in the road to the Farellones ski centre, along the Mapocho valley, in the northern end of the San Ramón range, obstructing almost a hundred metres of the road. Slow processes such as creep are also recognised, particularly in San Cristóbal hill and the slopes of the main ravines. The landslide activity in the western edge of the basin is restricted to creep in residual soils and small slides and flows in alluvial cones, generally of short runout and that do not pose an important hazard.

The Main Cordillera foothills, to the east and northeast of the city, show some important deposits of old mass movements (Fernández 2001). This area is characterized by heterogeneous materials form large blocks to clay that from a hummocky relief, next to old landslide scarps. These landslides are in general stabilized, but in some cases they may be partially re-activated by rain or earthquakes, as landslides or debris flows. Due to the distance from active volcanic centres, usually about or greater than 100 km, landslides related to volcanic activity are not common in the Santiago area.

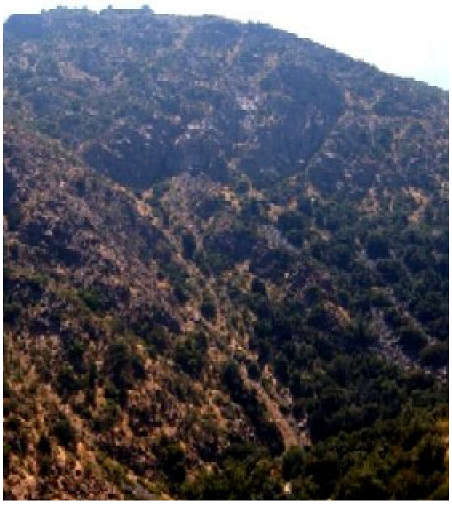

Figure 4. Above left: Panoramic view of Macul Ravine in its middle section. Note the small landslides in the slopes of the ravine. Above right: Deposits of a small debris flow in Lo Cañas Ravine, occurred in August 2005. Below: Rock fall in slopes of San Ramón Ravine.

LANDSLIDE HAZARD ASSESSMENT METHODS AND PRELIMINARY RESULTS

Current research by the authors aims to develop and implement landslide hazard assessment methods in Santiago. A brief overview of the methodological considerations and preliminary results related to the occurrence of rain-induced landslides are presented.

Hazard assessment methodology

Most of the landslide hazard studies in Chile have been and are still performed using qualitative or semi-quantitative methodologies, such as Field Geomorphological Analysis and Overlay and Combination of Index Maps with Weights (according to the landslide hazard assessment classification by Aleotti and Chowdury 1999). These studies are usually supported by some rough statistical analysis of rainfall or seismicity associated with the most recent events. The main problem of this method is that the evaluation of the hazard is totally or partially subjective, based on the scientist's experience. For example, a methodology for debris flow hazard assessment using the map overlay technique was proposed by Sepúlveda (2000). Most advanced methods, such as multivariate statistical analysis, geotechnical models or the use of neural networks are seldom used. The formulation of a new and more developed methodology that includes some of these techniques is now in progress, aiming to assess landslide hazards in Santiago and other cities. Some general aspects of this methodology are presented below.

The hazard assessment methodology is focused on the occurrence of landslides, flows and falls. This methodology is distributed on a wide quantity of phases that directly target the identification of critical susceptible zones and hazard assessment.

The first phase, based on desk studies, will allow the study zone to be delimited and the scale of the work to be established. The most important tool at this part is the review of aerial photography and geological information. The review of available bibliography and press records of historical events is also fundamental in this phase. With this data it would be possible to make an inventory of past landslide events in the zone of study, and to collect the necessary information that will enable the assessment of the slopes stability, such information includes the geology, geomorphology, geotechnical properties of soil and rock, hydrology, hydrogeology, seismicity, weather, vegetation and human activities. The aim of this part of the methodology is the identification of critical hazard zones and the triggering factors of past events.

The field phase is oriented to the characterization of soil and rock units present in the study zone, through geological and geomorphological mapping, collection of hydrologic and hydrogeological information, description of the vegetation, and performance of field geotechnical classifications, to check the identification of the critical zones and to collect samples for laboratory tests. With the latter we will be able to obtain material parameters for the development of stability models, such as soil granulometry, permeability, plasticity, unit weight and material strength.

This data will be used to generate geotechnical models and zonation, and for the stability assessment of the slopes through specific methods depending on the type of hazard event, such as limit equilibrium methods for landslides or hydraulic models to describe the behaviour of debris flows. Moreover, we consider multivariate statistical analysis of temporal distribution of landslide events associated with their triggering factors, as explained below.

The results will allow the generation of thematic maps (lithological, structural, geotechnical, geomorphological, and of slope stability) and susceptibility maps using spatial analysis in GIS. Furthermore, we consider the possible implementation of fuzzy logic or neuronal networks.

Finally, a hazard map of the study zone will be elaborated, with all the data stored in a GIS, establishing monitoring and mitigation recommendations and plans oriented to the community information and risk management.

Preliminary analyses of rain-induced landslide triggering factors

This part of the study consists of the performance of multivariate analyses with the purpose of obtaining a mathematical relationship that allows calculating the probability of a landslide event in the San Ramón Range. The range is considered for the analyses as a domain of similar geological and geomorphological characteristics, therefore the data from the range can be combined in a unique dataset. This is being made using the Logistic Regression Model, a nonlinear mathematical model, as described in González & Mayorga (2004). This model allows an expression to be obtained that relates a dependent variable *P(L)*, to several independent variables, which can be either binary or continuous. In general terms, the model has the form:

$$P(L) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \cdot x_1 + ... + \beta_p \cdot x_p)}}$$

where x_i are the independent or predictive variables and β_i are coefficients that adjust the model.

In this case, the dependent variable corresponds to the probability of occurrence of a landslide. The selection of the independent variables, which correspond to the landslide triggering factors, is based on the observations made in the area of study for past events. It is known that in Central Chile the main triggering agent of landslides are heavy rains, particularly precipitations of high intensity in a short time period (Hauser 1985, 1993, Naranjo & Varela 1996, Sepúlveda 2000), known as triggering rainfall. Additionally, we consider the antecedent or accumulated rainfall before the event, because these generally determine the soil strength conditions and response to the triggering rainfall (Terlien 1998, Glade 1998, Crosta 1998, González & Mayorga 2004, Ko Ko, Chowdhury & Flentje 2005). For the analyses, the triggering rainfall and the accumulated rainfall are considered as independent variables.

For the construction of the model, a rainfall record of daily precipitation from 1980 to 2003 at stations in Santiago located close to the mountain front, was used for the preliminary analyses. In this period, the occurrence of 5 landslide events triggered by heavy rain is recorded. The events are included as binary data for the dependent variable by assigning a value of 1 (unity) to days with events, and 0 (zero) to days without events, and then the regression is carried out. A series of regression models for different periods of accumulated rainfall, from 5 days to 30 days of accumulation was made. The goal is to find the model that maximizes the probability of the recorded landslide events. Preliminary results suggest that the accumulated rainfall that generally maximizes the landslide probabilities is 25 days. Furthermore, from the different models it is possible to determine that the adjusting coefficients related for the triggering rainfall are higher than those for the accumulated rainfall. This suggests that the triggering rainfall is more important than the accumulated rainfall for the occurrence of landslides in the area. Further analyses will include the position of the snow line, based on daily temperature records, as a predictive variable. This factor was found to be important in the major 1993 debris flows event. These statistical analyses will allow the definition of thresholds of the variables considered for the generation of landslides.

SUMMARY

Santiago, the capital city of Chile, is located in a basin along the edge of the Andes Main Cordillera, composed mainly by alluvial and fluvial sediments of generally good geotechnical behaviour, with exception of the western area which show poor seismic response in volcanic deposits. A rapid and insufficiently planned expansion in recent decades is increasingly exposing new housing estates to the hazard of landslides, especially debris flows that are generated in drainage basins of ravines that drain towards the city. A series of debris flow events have been recorded in the last decades, with an important correlation with the occurrence of the El Niño climatic phenomenon. The major debris flow event corresponds to a series of catastrophic flows in May 1993. Other landslide types are soil and rock slides and rock falls, of moderate impact in the city, triggered by heavy rains and earthquakes. The susceptibility to induce landslides is given by the structural and geotechnical characteristics of the Andes foothills next to the city, where deformed and strongly jointed rocks in steep slopes are prone to sliding, and to generate loose, coarse soil deposits which are remobilized during heavy rain events as debris flows.

Currently, a landslide hazard assessment methodology, including diverse qualitative and quantitative techniques of slope stability, susceptibility and hazard evaluation, is being developed and implemented in Santiago. Preliminary results on analysis of rain-induced landslides suggest that the rainfall on the day of the event is the most important triggering factor, while the accumulated rainfall is less relevant. These studies will allow generating landslide hazard maps that will be a useful tool for future urban planning in the city and other cities of similar geographical configuration around the country.

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