Andean Geology
ISSN: 0718-7092
ISSN: 0718-7106
andeangeology@sernageomin.cl
Servicio Nacional de Geología y Minería
Chile

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Andean Geology, vol. 45, no. 3, 2018
Servicio Nacional de Geología y Minería, Chile
Available in: https://www.redalyc.org/articulo.oa?id=173956934008
DOI: https://doi.org/10.5027/andgeoV45n3-3052

Nota Geológica

Landslide susceptibility maps of Santiago city Andean foothills, Chile

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DOI: https://doi.org/10.5027/andgeoV45n3-3052
Redalyc: https://www.redalyc.org/articulo.oa?id=173956934008

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Received: 10 January 2018
Accepted: 25 July 2018

Abstract:

he urban expansion of Santiago city includes areas with geomorphological and geological conditions with potential to be affected by landslide processes. This work presents compiled landslide susceptibility maps for the Andean foothills of Santiago city, between Maipo and Mapocho rivers. The maps identify the areas prone to the generation of slides, falls and flows. The results show that the oriental foothills of Santiago city have moderate to high susceptibility of rock falls, rock and soil slides and debris flows. The most important of these landslide types are debris flows, due to the runout of this processes that may reach urban areas posing a risk for the city, for which detailed hazard studies are required.

Keywords: Landslides, Slides, Debris flows, Rock falls, Susceptibility.

1. Introduction

Santiago city, in central Chile, has experienced in the last decades a sustained growth toward the Andean range foothills in the eastern fringe of the city, where landslide activity is most frequent. Occurrence of landslides in the mountain front and interior catchment hillslopes, and especially debris flows and mudflows that can reach the alluvial plain are common, and pose an increasing risk to populated areas (Antinao et al., 2003; Hauser, 1993, 2000). A large debris flow event in 1993 (Naranjo and Varela, 1996; Sepúlveda et al., 2006a, 2006b) is an example of the potential impact of catastrophic landslides in the area.

Most common landslide types in the area are debris flows that occur in several ravines and gullies that drain the mountain range toward the city; rock falls from steep, fractured rock slopes and slides, ranging from small volume shallow soil slides in colluvium to large, prehistoric rock megaslides in catchment headers. While heavy rainfall is the primary trigger of flows and shallow slides, other meteorological conditions such as the previous rainfall, the altitude of the 0°C isotherm and the occurrence of ENSO El Niño phase also have influence in the occurrence of landslides in the region (Hauser, 2000; Sepúlveda et al., 2006a; Sepúlveda and Padilla, 2008; Sepúlveda et al., 2015).

Seismic triggers cannot be ruled out, in particular due to the presence in the area of San Ramón Fault, a north-south trending reverse fault (Figs. 1 and 2) with recognized activity in the last 20,000 years (Rauld, 2011; Vargas et al., 2014; Díaz et al., 2014). Landslide activity due to large coastal thrust earthquakes typical of the Chilean plate margin such as the M 8.8, 2010 earthquake, appear to be limited in the area to rock falls and minor slides, due to the large distance to the seismic source (Sepúlveda et al., 2012; Serey et al., 2017). The effect of a third type of seismicity, intermediate depth intraplate earthquakes (Leyton et al., 2010) on landslide activity is not well known.

Documented historic events in the area producing damage have been mainly debris flows and hyperconcentrated flows in 1908, 1936, 1957, 1982, 1986, 1987, 1991, 1993, 2004, 2005 and 2009, plus some rock falls blocking roads during rain storms or earthquakes. Descriptions of such events can be found in Urrutia and Lanza (1993), Hauser (1993, 2000), Sepúlveda et al. (2006b), Lara (2007), Ferrando (2008) and Naranjo et al. (2009)1.

In this paper, we compile, revise and summarize landslide susceptibility mapping of the Santiago foothills performed by our research group over a number of years (Lara, 2007; Lara and Sepúlveda, 2010; SEREMI Metropolitana MINVU, 20132; Ceballos, 2015, and this work). These maps will provide a useful tool for decision makers on disaster prevention and territorial planning of the city in the future.

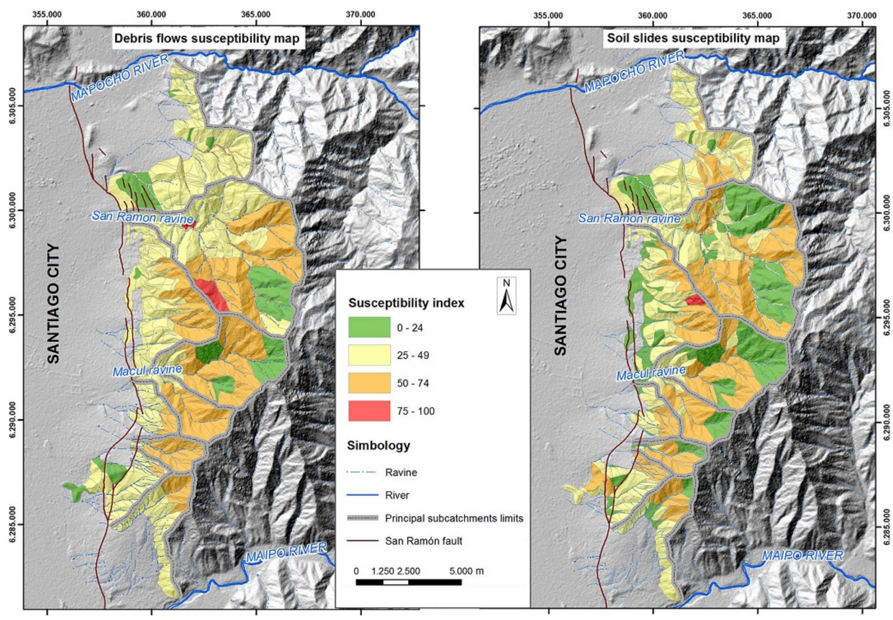

Fig. 1

Fig. 1. Susceptibility maps of debris flows and soil slides. Lara et al., 2018 (this work).

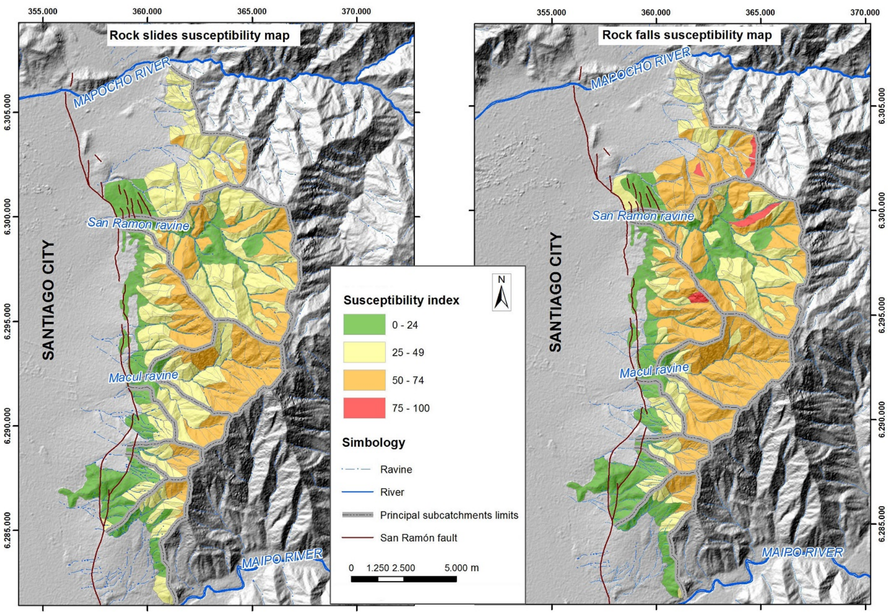

Fig. 2

Fig. 2. Susceptibility maps of rock slides and rock falls. Lara et al., 2018 (this work).

1 Naranjo, J.A.; Marín, M.; Fernández, J.; Falcón, F.; Huerta, S. 2009. Remociones en masa ocurridas el 6 de septiembre de 2009, en ruta G-21, Región Metropolitana (Unpublished report). Servicio Nacional de Geología y Minería: 17 p. Santiago.

2 SEREMI Metropolitana MINVU. 2013. Análisis Áreas de riesgo precordillera Etapa 2, comunas Peñalolén y La Reina. Technical report (Unpublished), Seremi Metropolitana de Vivienda y Urbanismo: 86 p.

2. Landslide susceptibility and conditioning factors

Landslide susceptibility can be defined as the propensity of an area to undergo landsliding (Glade et al., 2005). It may be assessed in general or to certain landslide type. A landslide susceptibility map depicts areas that have the potential for landsliding, determined by correlating some of the principal factors that contribute to the generation of landslides (Highland and Bobrowsky, 20083). Thus, a susceptibility map does not necessarily show all hazard areas, as it is focused on the source and not the areas potentially reached by the landslides. That difference with hazard maps is particularly important for long runout landslides such as debris flows and rock avalanches.

The larger the susceptibility, more prone is that area to be source of a landslide event. Susceptibility mainly relies on what we will name conditioning factors, a series of elements of the terrain that potentially contribute to slope instability. The conditioning factors are mainly those related with geomorphology (e.g., slope gradient and height), geology (e.g., rock or soil type, rock structure), geotechnical conditions (e.g., shear strength, saturation) and vegetation. As diverse landslide processes have different genesis and behaviour, the degree of influence of the conditioning factors may vary. For that reason, for medium-scale and local studies a susceptibility assessment differentiated by landslide type is preferable (Lara and Sepúlveda, 2010).

The Santiago city mountain front conforms the western edge of the Andean Cordillera, in the limit with the Central Depression where the city is settled. An impressive north-south trending range, visible from the entire city, runs between Mapocho and Maipo rivers, with peak altitude of 3,253 m a.s.l. (Mount San Ramón), over 2,000 m over the highest urbanized parts of the city. Above the 1,500 m a.s.l., the slopes in general have values between 30° and 50°, locally reaching values of 50°-70°. The rest of the slopes mainly vary between 20°-30°, and 5°-15° for plain areas with alluvial deposits. Over 30 catchments drain this range toward the city, with ravines and gullies that form alluvial fans in the foothills. This range is composed by Neogene volcanic and volcanosedimentary rocks of the Abanico Formation, of moderate to high shear strength, forming a rough relief with steep, rocky hillslopes, and little residual soil. The rocks are subject to water and ice action during winter, resulting in intense fracturing and generation of debris. This detritic materials form colluvial soil layers on the hillslopes and accumulate in drainage channels, with high potential of being removed (Fernández, 2001; Naranjo and Varela, 1996; Sepúlveda et al., 2006b; Ferrando, 2008). Intrusive rock such as dikes and sills form local bodies of differential strength and relief.

3 Highland, L.M.; Bobrowsky, P. 2008. The landslide handbook-A guide to understanding landslides. Geological Survey Circular 1325: 129 p. Reston.

3. Methodology

The susceptibility is calculated with a Susceptibility Index (SI), defined by Lara (2007) and Lara and Sepúlveda (2010). The methodology for its calculation is based on the addition of weighted ratings assigned to a list of conditioning factors, for the following landslide types: rock falls, rock slides, soil slides and debris flows. The original methodology was applied in the San Ramón ravine catchment in the Santiago city mountain front, the largest of the range (Lara and Sepúlveda, 2010), and later extended to the rest of the range between the Mapocho and Maipo rivers by a series of theses and a study by for the Housing Ministry. A second phase of the methodology proposed by Lara (2007) for hazard assessment using geotechnical software tools are out of the scope of this work.

The results of the application of this methodology is the elaboration of susceptibility maps, prepared on a GIS platform. We used a digital elevation model (DEM) with 9 meters resolution, elaborated by Rauld (2011), using diverse sources for topographic information, for the elaboration of a background shaded relief map, to be used as base for susceptibility maps, as well as for analysis of slope gradients. All the information is georeferenced on datum WGS 1984, 19S.

3.1. Susceptibility

The susceptibility analysis starts with the division of the catchment in terrain units, of similar geomorphological and geological conditions, defining zones of similar slope angles, orientation of slopes, geology, geotechnical properties, among other parameters. This is done combining information from a Digital Elevation Model (DEM) such as slope and aspect maps and the geological map, using Geographic Information Systems (GIS) tools and supported by photointerpretation. Each unit is defined by a polygon, in which is assigned a weighted rating for each conditioning factor following detailed tables for each landslide type (Lara and Sepúlveda, 2010. Appendix). The weighted ratings are recorded in the GIS attribute table for the terrain unit, and then added to obtain the Susceptibility Index of the terrain unit (SI), which is calculated such that the most critical condition has a score of SI=100.

As presented in Lara (2007) and Lara and Sepúlveda (2010), this score is based on the methodology for debris flow assessment developed by Sepúlveda (2000), updated and complemented for other landslide types (soil slides, rock slides and rock falls) from a bibliographic review and calibration with field observations by Lara (2007). This methodology consider those factors that control the generation of landslide processes. Higher ratings are given by geological, geotechnical and geomorphological characteristics of the terrain units. To optimize the process, slopes of less than 10º are disregarded for the SI calculations due to their very low probability of generating landslides.

The terrain units with SI≥50, chosen as a threshold or critical value, are considered as susceptible, and should be prioritized for subsequent specific hazard analyses. The SI=50 threshold was arbitrarily established, by means of calibration of susceptibility scores with observed landsliding in the San Ramón Ravine.

The SI values are represented by colours, using 25 points tiers as proposed by the methodology authors. An SI value over 50 means a high or very high (SI>75) susceptibility. For these landslides prone units a hazard assessment based on slope stability and runout analyses is recommended (Lara and Sepúlveda, 2010).

4. Results and discussion

Figures 1 and 2 show the consolidated susceptibility maps for the four landslide types in the whole western slope of the San Ramón Mountain range between Mapocho and Maipo rivers in eastern Santiago. Original maps were made on scale 1:20.000. Areas not coloured have slope gradients below 10° and are not included in the susceptibility index calculations. These maps show only those areas with potential of generation of different types of landslides, i.e., susceptibility. Other factors such as the runout and volume calculations, areas of deposition or entrainment of materials along their paths, especially for flow processes that have long runout reaching areas far from the source, are not part of the results, as they are part of hazard analysis.

In general, it can be observed that very high susceptibility values (IS>75) are restricted to a few areas, while moderate to high values (between 50 and 75) dominate the catchment areas. Low to null susceptibility areas are highly variable depending on the landslide type, as they are highly dependent on the local geology and slope gradient.

Soil slides higher susceptibility (mostly 50>IS>75) are found in the middle sections and headers of creeks in San Ramón catchment and some smaller ravines such as Nido de Águilas, Peñalolén, Santa Rosa and Las Vizcachas (Figs. 1 and 2), whereas in the Macul catchment susceptible zones are mainly hillslopes of secondary creeks. The only very high susceptibility area (IS>75) is located in the headers of the small Peñalolén catchment.

A relatively similar pattern is found for debris flows (Fig. 1), as those triggered initially as soil slides are considered in the methodology, with addition of the presence of drainage channels on footslopes as units with potential to transport detritic materials. Nevertheless, lower susceptibility values are found in the northernmost Apoquindo catchment, while higher susceptibility is concentrated in the San Ramón and Macul catchments and those smaller ones between them and south of Macul, with some local areas of very high susceptibility. It must be noted that flows indirectly produced by channel damming by trunks, garbage or other landslides are not considered in these results.

Rock slides and rock fall high susceptibility zones tend to coincide with higher gradient hillslopes (Fig. 2). Rock fall high susceptibility is widespread, although in the field it is observed that is generally related with localized rock outcrops, not well captured by the mapping scale of the terrain units, and thus the surface areas of high susceptibility in this case are somewhat overestimated. Some higher rock fall susceptibility areas are found in catchment headers of Apoquindo, San Ramón and Peñalolén ravines.

Those higher landslide susceptibility areas are generally not located in the urbanized land, which expand to the mountains front foothills and the piedmont formed by the alluvial fans, but not much into the interior catchments hillslopes and headers. That implies that the runout of the potential landslides, not shown on susceptibility maps, is key to assess the hazard and risk for the city. For that reason, even there is an important potential for slides and rock fall activity in the catchments, debris flows are the most risky, given their long runout distances that reach the large alluvial fans where urban expansion has taken place in the last decades. So far, construction is restricted by urban planning into the catchments over 1,000 m a.s.l., which will keep other landslide types risk constrained as long as those restrictions remain in place.

5. Conclusions

We compiled, revised and summarized landslide susceptibility mapping of the Santiago city foothills, where susceptibility is calculated with a quantitative Susceptibility Index (SI). The methodology for its calculation is based on the addition of weighted ratings assigned to a list of conditioning factors, for the following landslide types: rock falls, rock slides, soil slides and debris flows.

Moderate to high susceptibility values (SI between 50 and 75) dominate the catchment areas. Higher values are only local. Low to null susceptibility areas are highly variable depending on the landslide type, as they are highly dependent on the local geology and slope gradients.

Landslide susceptibility is mainly found in the interior catchments hillslopes and headers, in areas that are in general not urbanized. Urban areas expand in the mountain front foothills and the piedmont formed by alluvial fans, zones that have already been affected by important debris flows generated on catchment headers on last decades. That implies that the runout of the potential landslides, particularly of debris flows, though is not considered in the susceptibility analysis, is key to assess the hazard and risk for the city.

Acknowledgements

The results shown in this work have been funded by Fundación Andes grant C14060/14 (Chile), Chile Housing and Urbanism Ministry, Conicyt-Fondecyt grant 1140317 (Chile) and NERC-Newton fund grant NE/N000315/1.

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Appendix

Charts for calculation of susceptibility index (SI)

Factor	Condition	Score	Factor	Condition	Score
Slope angle (f_1)	15°-20°	9	Snow accumulation (f_5)	Null	0
	20°-25°	15		Sporadic	1
	25°-30°	21		Seasonal	2
	30°-40°	26		Permanent	5
	>40°	30	Vegetation (f_6)	High	0
Sunlight exposition (f_2)	Low	1		Moderate	2
	Partial	3		Low to null	5
	High	5	Artificial intervention on slopes (f_7)	Not observed	0
Geological-geotechnical characteristics of slope materials (f_3)	Very unfavourable	2		Little important	5
	Unfavourable	6		Important	10
	Partially favourable	10	Declared slides on slope (f_8)	Not observed	0
	Favourable	14		No records	3
	Very favourable	20		Present	10
Moisture and saturation conditions (f4)	No records	2	Declared slides on unit (f_9)	Not observed	0
	Unfavourable	3		No records	2
	Favourable	7		Present	5
	Very favourable	10			

SOIL SLIDE CONDITIONING FACTORS SCORING FOR SI (LARA AND SEPÚLVEDA, 2010).

Factor	Condition	Score	Factor	Condition	Score
Slope angle (f_1)	15°-20°	11	Snow accumulation (f_3)	Null	0
	20°-25°	15		Sporadic	1
	25°-30°	20		Seasonal	2
	30°-40°	25		Permanent	5
	40°-60°	30	Artificial intervention on slope (f_4)	Not observed	0
	>60°	35		Little important	5
Geological-geotechnical characteristics of slope materials (f_2)	Very unfavourable	4		Important	10
	Unfavourable	11	Declared slides on slope (f_5)	Not observed	0
	Partially favourable	18		No records	5
	Favourable	28		Present	15
	Very favourable	35			

ROCK SLIDE CONDITIONING FACTORS
SCORING FOR SI (LARA AND SEPÚLVEDA, 2010).

Factor	Condition	Score	Factor	Condition	Score
Slope angle (f_1)	10°-15°	3	Moisture and saturation Conditions (f_6)	No records	2
	15°-20°	6		Unfavourable	3
	20°-25°	9		Favourable	7
	25°-30°	11		Very favourable	10
	30°-40°	13	Snow accumulation (f_7)	Null	0
	>40°	15		Sporadic	1
Drainage channel angle at slope foot (f_2)	<5°	1		Seasonal	2
	5°-10°	5		Permanent	5
	>10°	10	Vegetation (f_8)	High	0
Flow confinement (f_3)	Low	1		Moderate	3
	Medium	4		Low to null	5
	High	7		Not observed	0
Sunlight exposition (f_4)	Low	0	Drainage channel obstruction (f_9)	Low	2
	Partial	2		Moderate	4
	High	3		Important	5
Geological-geotechnical characteristics of slope materials (f_5)	Very unfavourable	3	Artificial intervention on slope (f_{10})	Not observed	0
	Unfavourable	8		Few important	3
	Partially favourable	13			
	Favourable	18		Important	5
	Very favourable	25			
Declared flows in basins (f_{11})	No records	1			
	Prehistoric	4			
	Historic, low frequency	7			
	Historic, high frequency	10			

DEBRIS FLOW CONDITIONING FACTORS
SCORING FOR SI (LARA AND SEPÚLVEDA, 2010).