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Shallow-seated landslide susceptibility and hazard assessment in volcanic edifices from an engineering geological approach: Case of study – Llaima volcano

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ABSTRACT:

Landslides are one of the most important geological hazards in South America, especially in mountain environments, such as The Andes in Chile. The geological, geomorphological, tectonic, and climatic conditions of Chile, characterized by the presence of the Andean Mountain range with active volcanoes, impose a high susceptibility to generating different types of mass movements. Furthermore, mass movements can occur alone or, in many cases, associated with cascading hazards. This research aims to explore the cascading hazard in the volcano environment, particularly at Llaima volcano. The Llaima Volcano (38°42'S, 71°44'W), located in the Southern Andes Volcanic Zone (ZVS) of the Araucanía region, is one of the most active volcanoes in South America, with intense eruptive activity and abundant occurrence of landslides and lahars during the last centuries. This work seeks to evaluate landslide hazards based on a methodology that combines the determination of landslide susceptibility, calculated by integrating conditioning factors with assessing slope failure and incorporating geotechnical engineering approaches. This method can be used in other volcanic areas for applications for volcanic risk, territorial planning, engineering, and environmental purposes.

KEYWORDS: landslides, susceptibility, cascading hazard, volcanic debris flows, Llaima volcano.

1 INTRODUCTION.

Landslides are among the most recurrent geological hazards (Bradd & Harrod, 1989) and can occur alone or, in many cases, develop sequences of cascading hazards (Fan et al., 2019). Mass removals have a high impact in South America, especially in mountain environments such as the Chilean Andes (Moreiras & Sepúlveda, 2015; Serey et al., 2020). In fact, in tectonically-active mountain areas, landslides are a major cause of fatalities and economic losses (e.g. Jibson et al. 2006; Sato et al., 2007; Qi et al., 2010; Dai et al., 2011).

The geological, geomorphological, tectonic, and climatic features of Chile, characterized by the presence of the Andean orogen alongside a quasi-continuous volcanic arc, impose a high susceptibility to generating different types of mass movements, such as rock and soil slides, flows, and falls. In this respect, the relationship between volcanic activity (e.g., magma intrusions, eruptive styles, and their products) and the productivity of shallow-seated landslides (also called thin-skinned, i.e., a few to hundred meters deep) remains poorly understood (Romero et al., 2021) and is not considered in volcanic hazard evaluation. Therefore, in addition to the primary volcanic hazard assessment for active volcanoes, it is essential to assess a multi-hazard evaluation that integrates landslides.

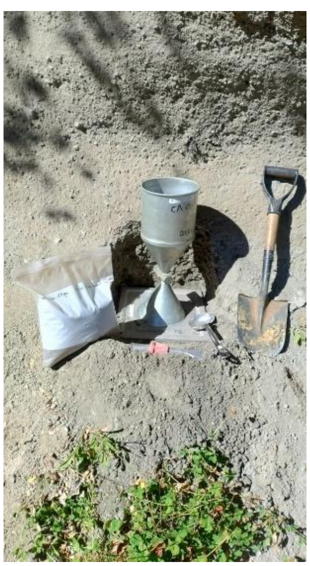
This research aims to explore the cascading hazard at Llaima volcano (38°42'S, 71°44'W), located in the Southern Andes Volcanic Zone (ZVS) of the Araucanía region. It is one of the most active volcanoes in South America and ranks 3rd in the Chilean volcanic threat ranking (Sernageomin, 2023), with frequent eruptive activity in historical times (<500 years BP) and abundant occurrence of landslides and lahars during the last centuries. This work seeks to evaluate landslide hazards based on a methodology that combines landslide susceptibility, calculated by integrating conditioning factors, with the assessment of slope failure and runout probabilities, incorporating geotechnical engineering approaches. This method is envisaged to be used in other volcanic areas with applications for volcanic risk, territorial planning, engineering, and environmental purposes.

2 METHODS

Methodologically, systematic steps were conducted to recollect geological and geotechnical information based on fieldwork, geotechnical tests and bibliographic reviews.

First, based on Salgado (2022), a preliminary geological map was prepared by reviewing existing maps, literature, historical press data, and photo interpretation to be checked and completed in the field. The map provided the information for bedrock as soil deposits and a complete geomorphological description of landforms. Additionally, a landslide inventory was prepared by visually interpreting high-resolution remote sensing images from satellites. Subsequently, landslides were verified and mapped during a field trip.

During fieldwork in February 2024, geotechnical and structural information on the rock mass and soil deposits was collected. We obtained intact rock samples and soil samples for laboratory analysis from the accessible outcrops. The in-situ soil density assessment by the sand cone method (ASTM D1556-64 standard) and the determination of rock hardness by rebound hammer method (ASTM D5873 Standard) tests were achieved from natural outcrops (Figure 1).



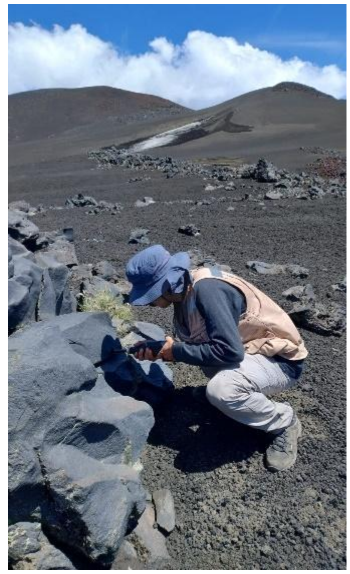


Figure 1. Geotechnical tests from natural outcrops. Left, in-situ soil density assessment by the sand method. Right, rebound hammer method test.

In the geomechanics laboratory of Universidad de O'Higgins (Figure 3), we measured the point load strength, Is(50), of intact block samples according to the ASTM 5731 standard; using the point load data, we estimated the Unconfined Compressive Strength (σ_{UCS}). Consolidated-drained triaxial tests of remoulded soil samples were developed to determine shear strength parameters.

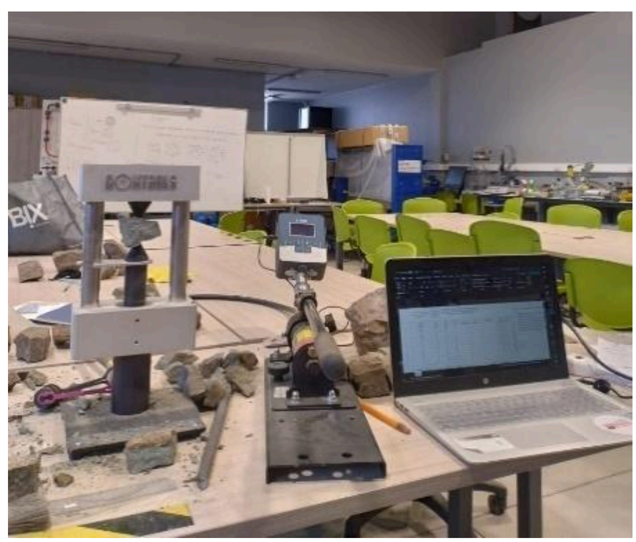


Figure 3. The point load strength tests in the Geomechanics laboratory of Universidad de O'Higgins.

After all the geological and geotechnical information was collected, the susceptibility was evaluated in each pixel by a sum of weighing conditioning factors with the use of Geographic Information Systems (GIS) for the following landslide types: rock falls, rock slides, soil slides, and volcanic alluvium. The susceptibility is calculated with a Susceptibility Index (SI, ranging between 0 and 100) developed by Lara (2007) and Lara and Sepúlveda (2010), updated and complemented by a bibliographic review and calibration with field observations. These methods consider as conditioning factors the slope angle, geological-geotechnical characteristics of slope materials, proximity to the known mapped seismic faults, snow accumulation, moisture and saturation conditions, vegetation, sunlight exposition, and declared landslides on the slope. The weight of conditioning factors depends on the mass movement. SI value over 50 means high susceptibility or very high (SI>75). The method is appropriate for a medium or regional scale (1:25,000). All the information is georeferenced on datum WGS 1984, 19S.

The hazard assessment is based on the combination of failure and runout probabilities, each obtained separately for different types of landslides, derived from diverse criteria. The failure probability analysis is carried out for each morpholithotechnical unit with SI>50, using numerical and computational tools and under scenarios considering saturation conditions. The geotechnical field observations and laboratory testing results of rock and soil samples are used as input material properties data for software-based slope stability analyses. Also, the geometry of representative slopes for each terrain unit is required, particularly data on slope angle, slope height, and upper slope face angle, which are obtained from a representative topographic profile of the unit using GIS tools.

3 RESULTS

Applying the methodology described above, the susceptibility was computed, resulting in four susceptibility maps, one for each type of studied landslide (soil slides, rock slides, volcanic debris flows and rock falls). Areas with steep slopes, lower geotechnical quality of the geological material and closer to observed seismogenic faults and parasitic vent alignments represent the highest SI values. The susceptibility for generating volcanic debris flows is the highest in areas mainly restricted to the waterheads of the local drainage basins; however, there are some zones at lower elevations in which high susceptibility is associated with steep slope angles and the pre-existing accumulation of epiclastic unconsolidated material. By combining failure and runout probabilities (using Slide2, Rocfall and HEC-RAS softwares), relative landslide hazard degrees have been determined for each studied landslide, resulting in landslide hazard maps for the worst-case scenario; for each analysis, a scenario of heavy rainfall was assumed. In the case of shallow soils, the condition of full saturation was assumed. Subsaturation was considered for soils or rock slopes, with the water level a few metres below the topographic surface. Almost all slopes adjacent to ravines with a critical slope angle (generally 30° on average) show shallow-seated landslide hazard, which typically result in high, with only a few exceptions.

A landslide hazard assessment has been therefore carried out for Llaima volcano on the definition of qualitative susceptibility, including geotechnical approaches to assess failure and runout probabilities. The results show that the main landslide hazards are volcanic debris flows, rockslides, rock falls, and shallow soil-seated landslides. The landslide hazard assessment in volcanic edifices at a detailed scale using the presented methodology has critical applications for volcanic hazard evaluation, territorial planning, baseline environmental studies, and feasibility studies of engineering projects, among others.

4 CONCLUSIONS

This investigation in the Araucanía region, Southern Andes Volcanic Zone, evaluates the shallow-seated landslide susceptibility and hazard assessment of Llaima volcano. The landslide susceptibility methodology is based on the sum of the weight of conditioning factors (slope angle, geological-geotechnical characteristics of slope materials, proximity to the known mapped seismic faults, snow accumulation, moisture and saturation conditions, vegetation, sunlight exposition, and declared landslides on the slope). The hazard assessment of Llaima volcano is based on the combination of failure and runout probabilities. The results support the integral risk cycle of landslides in volcano edifices.

5 ACKNOWLEDGEMENTS

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