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# Methodology for quantitative landslide risk analysis in residential projects

Paola Andrea Isaza-Restrepo [b], Hernán Eduardo Martínez Carvajal [b, c],
Cesar Augusto Hidalgo Montoya [a, b, *]

[a] Civil Engineering Program, Universidad de Medellín, Carrera 87 N° 30 – 65, Medellín, Colombia
[b] Posgraduação em Geotecnia, Universidade de Brasília, Brazil
[c] Departamento de Ingeniería Civil, Universidad Nacional de Colombia at Medellín, Colombia

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This paper provides a quantitative assessment for the hazard, the vulnerability and the risk associated to slope instability as a tool for urban planners and policy makers. Analysis methodologies and overall numerical procedures are presented in detail. In order to assess a hazard, which is expressed as a temporal probability, FOSM technique was used along with Rosenblueth's point estimate method. Reliability index ($\beta$) was used as a standard measure to compare the results assessed with other information presented in published literature for a number of geotechnical projects. Concerning the analysis of vulnerability, a new approach was proposed by combining local methodology for seismic vulnerability designed for buildings in Medellin with generic analysis methodology for vulnerability of people when exposed to landslides. The risk was assessed by a simple mathematical crossing between hazard and vulnerability. A database of 120 residential projects located on natural slopes in the city of Medellin (Colombia) was used for the analysis. The results were presented as FN charts relating the calculated frequency of landslides to the number of potential life or economic losses.

## 1. Introduction

Landslides and slope stability are important issues to consider in planning cities located in mountainous regions. In regions where urban residential areas coincide with mountainous terrains, the risk is higher for people and the economic costs include relocating communities, repairing physical structures, and restoring water quality in streams and rivers (Dragicevic, Lai, & Balram, 2015). In many developing countries, where the land occupation is almost always done in a disordered way, the largest growth of cities occur in landslide prone areas to its geographical and geological conditions. This occupation model is one of the main causes of problems in urban hillside areas because at those areas the population lives under constant disaster threats (Saboya, Alves, & Pinto, 2006). Particularly in areas of South Asia and South America, the populations are often concentrated in deep valleys prone to catastrophic landslides, as is the case of large Latin American cities such as Rio de Janeiro, Caracas and Valparaiso (Sepúlveda & Petley, 2015). The territory of Valle de Aburra valley (Colombia), can be included in this set of urban areas. In the last four decades, landslides have been recurrent, countless and tragic in this densely populated area, as a consequence of the accelerated and most of the times disordered occupation as well as the geological and geomorphologic complexity of this region (Aristizabal & Gomez, 2007).

Although it is not common to find statistical data of deaths and economic losses due to landslides (Klose, 2015), with an estimated 60.501 deaths and 3.759.329 homeless in the 20th century, landslides rank sixth in number of deaths and fourth in number of homeless worldwide between natural hazards (Bryant, Head, & Morrison, 2005) (Chowdhury, Flentje, & Bhattacharya, 2010). Meanwhile, Latin America and the Caribbean in the period 2004–2013 recorded 611 landslides that caused 11.631 deaths, mostly as a result of rainfall triggers (Sepúlveda & Petley, 2015). The geographic distribution of the landslides is heterogeneous, but mostly reflect the combination of relief, precipitation and population density. In urban areas, the presence of informal settlements have a big impact on the number of fatalities, showing the effect of

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* Corresponding author. Universidad de Medellín – Civil engineering Program, Carrera 87 N° 30-65 (Bloque 4), Medellín, Colombia.
*E-mail addresses:* chidalgo@udem.edu.co, chidalgom2009@gmail.com (C.A. Hidalgo Montoya).

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poverty and marginalization (Klose, 2015). Table 1 shows an estimation of the direct and indirect costs of landslides in different countries and Fig. 1 shows the consequences in deaths and economic losses for Aburra Valley according to data collected from 1880 to 2007.

In recent years there have been several landslides that have caused numerous deaths and economic losses. Table 2 shows some selected landslides for its great impact worldwide and also in the case study area. Most of these events occurred in areas of irregular occupation; however, slopes of formal projects have also presented problems (Isaza-Restrepo, 2011). More disturbing than natural slopes are the slopes produced by the activities of urban projects which have unknown risk levels and have already caused problems in the past.

Control of such events became a priority for public administrators of cities in mountain regions all over the world. Nevertheless, a lack of organized urban development with clear, rational delimitation of zones susceptible to mass movements results in occupation of inadequate areas, creating high risk scenarios for life and material assets (Klose, 2015; Saboya et al., 2006; Vélez, Hoyos, Vélez, & Gómez, 1993). In this context, the need to develop new methodologies or to adapt existing ones is clear in order to better understand the conditions that cause landslides in mountain regions and to create planning tools that allow better management of occupation processes on natural slopes.

This paper presents a methodology for quantitative risk assessment of landslides. As a study case, the methodology was applied to 120 critical places on natural slopes of Medellin. It was conducted based on a database drawn up by soil mechanics studies for various projects. Pluviometric records, geotechnical database, and architectonic and socioeconomic information of the projects, such as structural type, population density, gross national product (GNP), inhabitants' age distribution and property value were used in the study. The analysis and calculation methodology of the factors involved are presented in a general manner, and was developed by Isaza-Restrepo (Isaza-Restrepo, 2011) based on studies by Botero-Fernandez (Botero-Fernández, 2009) and Uzielli et al. (Uzielli, Nadim, Lacasse, & Kaynia, 2008). The former is used to assess the physical vulnerability of buildings exposed to seismic hazard and the latter to quantify the vulnerability of people inside and outside of buildings in places affected by landslides. This quantification of the vulnerability represents a major input for the risk assessment models. Once the risk is quantified, the way to the definition of the acceptance criterion is straightforward. In engineering as in other aspects of life, lower risk usually means higher costs. Thus, the policy makers are faced with the question, "how safe is safe enough," or "what risk is acceptable?" (Baecher & Christian, 2003). It is commonly accepted that governmental policies about the risk analysis decisions are necessary in order to legitimize the technical methodologies; nevertheless, the public consensus is absolutely necessary to validate the policy. In Colombia and other countries in Latin America, government officials have not defined the acceptable levels of risk for civil infrastructure. The definition of reasonable risk levels (acceptable levels) is left up to local agencies. The procedures for calculating the vulnerability and the risk for civil projects are different from one agency to another. On the other hand, the criteria used to separate acceptable risks from unacceptable risks, vary from qualitative to quantitative, depending on the specific activity of the agency. This paper is intended as an aid to technicians and policy makers to better understand the physical vulnerability in order to improve their procedures for risk assessment methodologies.

**Table 1**
Total annual losses caused by landslides in different countries worldwide (Klose, 2015).

| Country | Total annual loss (USD billion) | Loss as percentage of GDP |
|---|---|---|
| USA | 2.1–4.3 | 0.01–0.03 |
| Japan | >3.0 | >0.06 |
| Italy | 3.9 | 0.19 |
| India | 2.0 | 0.11 |
| China | >1.0 | 0.01 |
| Germany | 0.3 | 0.01 |

## 2. Risk assessment methodology

There are several approaches to assess risk, particularly geotechnical risk. Cardona (2001) shows a detailed review over risk assessment methodologies associated to seismic hazard. Einstein and Sousa (2006), however, discuss the problem of risk assessment making it possible its insertion in alert systems against different types of natural hazards. Despite the great volume of technical literature about the subject, there is no universal analysis and calculation technique in terms of methodological agreement yet. The most important accepted approaches are the quantitative, the holistic and the qualitative ones.

In regards to quantitative methods, it can be highlighted the proposal of Einstein and Sousa (2006). According to it, risk can be defined as the product of the probability of occurrence of a catastrophic event ($P[T]$) meaning hazard, and damage costs $u(C)$ *due to the occurrence of the catastrophic event,* meaning vulnerability (Eq. (1)).

$$R = P[T] \times u(C) \tag{1}$$

Both qualitative and quantitative approaches are suitable depending of the precision aimed, of the problem nature and of the compatibility between quality and quantity of the data available the three approaches are suitable. Usually, for a great area where data quality and quantity are poor, a risk qualitative assessment may be more suitable, whereas for a natural slope of a specific place, the hazard analysis may be carried out through quantitative assessment (Dai, Lee, & Ngai, 2002). This last approach represents the case presented in this research, in which several slopes of real urban projects in the city of Medellin are analyzed.

Following, the hazard and vulnerability methodologies for analysis will be presented and by crossing these two variables, the result achieved is risk, represented as economic or life losses.

### 2.1. Hazard analysis

The definition of hazard gathers the concepts of magnitude, geographic localization and recurrence time (Guzzetti, Carrara, Cardinali, & Reichenbauc, 1999). Magnitude refers to the dimension or intensity of the natural event; geographic localization implies the capability to identify the place where the event may occur; recurrence time refers to the event's temporal frequency. In order to be determined, the probability of magnitude requires a representative sample of real landslides data (inventory) that can be statistically measured to obtain the geometric characteristics of the events and to create models which have the capability of prediction. Inventories with sufficient broad characteristics are scarce, reason why the analysis of this probability of magnitude is so hard until today. On the other hand, the methodologies to assess spatial probability are more abundant due to the fact that the environmental factors which determine landslides are well-known, such as geology, geomorphology and soil use. These factors combined with simple inventories, in which only the place and the date of occurrence are determined, make the calculation of this type of spatial probability easier. Finally, temporal probability necessarily involves