Statistical Approaches for The Assessment of Landslide-Related Economic Losses

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Abstract. In this paper, different statistical approaches are employed to consider several scenarios of hazard and infrastructure vulnerability to measure the magnitude of the mass movement and quantify the economic costs. In this context, we employ the techniques of simulation bootstrap, Monte-Carlo and variance reduction in the context of Monte-Carlo in order to compare the values of the economic losses before a potential disaster in an objective, standardized and reproducible way. With the purpose to explain the proposed methodology, a case study located in one of the most landslide-prone zone of the city of Medellin-Colombia is analysed, comparing different structural scenarios for a total of 48444 exposed buildings. Also, different seismic scenarios of landslide hazard were considered, varying the horizontal acceleration (Ah) that can act as one of the triggers of the mass movement. The novel proposed methodology permits to obtain an estimation of the probable economic losses by a certain landslide, and also to get better assessments by reducing the uncertainty and compare the results between different statistical approaches, taking into account the uncertainty of the exposed building costs. It is important to mention that between the simulated scenarios the better results are shown in the bootstrap simulation and Monte-Carlo simulation with reduction of variance. The analyzed simulation methodologies provide a better estimation of economic losses for horizontal acceleration of ground between 0 g and 0.3 g. It is noticed an economic reduction of on the order of 7%, 14% and 21% in the structural scenarios 2, 3 and 4 respectively, in comparison with the current structural condition of the exposed buildings, in case of a landslide triggered by an earthquake with the maximum expected horizontal acceleration for the city.

1. Introduction
Natural disasters of a geodynamic nature like mass movements occur extensively around the world with economics consequences and fatalities greater than any other natural disaster. Due to this reason, the study of landslides is worldwide matter of interest to the planning of cities, particularly in mountainous regions where both people and infrastructure are more exposed and the landslide risk is higher.

In recent decades, the number of reported natural disasters and their impact on human and economic development worldwide has increased. Indeed, over the past 40 years, natural disasters have caused more than 3.3 million deaths and US$ 2.3 trillion in economic damage [1]. Globally, 14% of
economic losses and 0.53% of deaths from disasters caused by natural phenomena are landslides related, with estimated economic losses over $1 billion in many countries. In Colombia, disasters have caused losses of approximately US$ 7.1 billion in the same period, representing an average of US$ 177 million annual losses. At the local level, specifically in the Aburrá Valley (AV) where is located the city of Medellin, it is estimated that about 35% of the damage to buildings and 74% of deaths natural phenomena are landslides-related, which contrasts worryingly with the losses reported worldwide [2].

In developing countries with tropical mountainous regions, rainfall-induced landslides occur almost every year causing huge economic and human losses, and quantifying landslide hazard and other risks associated with heavy rainfall is important, because landslides cause damage to property and loss of human lives. Due to high levels of impact of landslides, this has generated a great interest in the study of related phenomena in an attempt to understand physical aspects, and economy-related issues [3].

Municipal authorities in charge of the planning of cities in these countries need to develop investment plans for the prevention and mitigation of disasters by landslides, for which they must allocate an important budget item. For this reason, it is convenient to carry out quantitative risk analysis (QRA), which allows estimating the level of damage and the associated economic consequences. A QRA can take into account the uncertainty of the infrastructure costs, in order to perform cost/benefit analysis between preventive measures of a landslide and post-disaster management actions, allowing optimizing interventions to bring the risk levels to an acceptable level and encouraging authorities to invest resources in the most landslide-prone areas. For example, several statistical approaches can be used to consider many scenarios of hazard and infrastructure vulnerability to measure the magnitude of the landslide and to quantify the economic costs.

In this paper, it is employed the techniques of simulation bootstrap, Monte-Carlo and variance reduction in the context of Monte-Carlo in order to compare the values of the economic losses before a potential disaster in an objective, standardized and reproducible way. The application of the proposed methodology for quantifying risk was used in a study case located in one of the most landslide-prone zone of the city of Medellin-Colombia, comparing both different seismic scenarios of landslides and structural scenarios of exposed buildings.

2. Materials and Methods

2.1. Quantitative Landslide Risk Analyses

A quantitative risk analysis (QRA) can be carried out for different types of processes (debris flow, slow mass movement, rapid mass movement, and rockfall), different triggering events (rainfall, earthquake, and anthropogenic processes), different physical and environmental context, and for different objectives and scope of the analysis. [4] classify these approaches regarding the way they estimate the risk based on the level of quantification in: qualitative, semi-quantitative and quantitative methods. Generally, for large areas where the quality and quantity of available data are too scarce for quantitative analysis, qualitative or semi-quantitative risk assessment are carried out, while for site-specific slopes that are often characterized by many observation data on hazard and past damage, detailed quantitative risk assessment should be carried out [5].

A quantitative approach requires information about hazardous processes, like the temporal, spatial and intensity probability, this include their triggers as well as their landslide run-out. As well, it is important an estimation of the physical consequences caused by the hazard in the elements at risk, habitually quantified in monetary values taking into account their vulnerability by assessing the conditional probability of the consequences occurring given the occurrence of a hazard.
One of the main advantages of a QRA is that it can be compared with other types of risk that can affect a community and because of its quantitative nature it can be communicated more comprehensibly to the policy and decision makers to be used for risk management strategies [4]. In most cases, a pure quantitative assessment is difficult. This is due to the complexity of the problem, the lack of sufficient statistics on past landslide fatalities and losses, and the absence of documented reference events of a given landslide type for the studied region [5].

In quantitative evaluation of landslides risk, it is necessary to estimate the hazard (H), the vulnerability (V) and the consequences that can be determined as the probability of death or the magnitude of the economic losses (C). For this paper, the risk (R) is assessed with the following expression:

\[ R = H \times V \times C \]  

In this methodology, H was calculated through a probabilistic framework for hazard assessment, which uses methods as first order second method (FOSM) and failure thresholds. Also, different seismic scenarios of landslide hazard were considered, varying the horizontal acceleration (Ah) that can act as one of the triggers of the landslide. The vulnerability was taken as the physical vulnerability for four structural scenarios of buildings. “Scenario 1 (S1)” includes the current structural condition, “Scenario 2 (S2)” corresponds to a structural type in which masonry was the weakest material, “Scenario 3 (S3)” consisting of any structural type with stiffening elements, and finally “Scenario 4 (S4)” involves a structural type of supporting walls with stiffening elements, which fulfills the minimum structural requirements of Colombian building code -NSR10-.

For this paper, the general procedure for the QRA approach considers an unfavorable condition for building analysis by the effect of a potential landslide. The used methodology evaluates the failure probability of the terrain where buildings are settled, causing a damage in buildings (Figure 1). Because this paper is devoted to assess economical losses, the hazard and vulnerability results were taken from [9]. The cost of losses (C) is determined considering the costs of construction as such, and the cost of land where the building sits, using the following methods.

\[ \text{Urban Planning Guidelines} \]
2.2. Statistical techniques for economic losses assessment
The economic losses associated with landslide activity may be obtained by the single product between physical vulnerability and economic value for any exposed element. According to [6], the value of elements at risk may be expressed in three different ways: monetary value, which is the price or current value of the asset, or the cost of its replacing with a similar or identical asset; intrinsic value, which measures the importance and the irreplaceable character of the asset; and utilitarian value, which measures the usefulness of the asset.

Two different approaches are used to express economic loss starting from this mathematical relation: the first one, using continuous values illustrated as cumulative probability of loss, and also discrete (minimum and maximum) values of loss [7]. In the last case, the monetary value of the buildings can be assessed by calculating a discrete value for each individual building based on cadastral values ([6]; [8]; [9]), real estate values ([10]; [11]), and reconstruction costs ([12]; [13]). Since real estate values and reconstruction costs, may be very volatile at the short time [8], the cadastral values to compute the buildings values (EV) were used in this evaluations. Cadastral value of buildings in Medellin is calculated taking into account the historical values of the market, the area of the parcel and construction, the type, use, occupation and function of the buildings, structural and constructive characteristics of the buildings, quality of the building materials and their state of conservation.

2.2.1. Bootstrapping simulation. The bootstrap simulations of statistical models are commonly used to characterize empirical landslide parameters distributions. The bootstrap is a data-based simulation method for statistical inference. It is a conventional stochastic simulation, but the difference is that in conventional simulation the data are constructed artificially. In contrast, bootstrapping is used to obtain a description of the properties of empirical estimators by using the sample data points, and it involves sampling repeatedly with replacement from the actual data in order to simulate the underlying data-generating distribution.

Then, the distribution is approximated by the data without making any parametric distributional assumption. This is a non-parametric computational estimation technique that permits an application of the plug-in principle, using the available data with bias-reduced error estimation [14].

2.2.2. Monte Carlo simulation. Monte-Carlo simulation can be used in order to describe a given means of propagating uncertainties in the inputs of a model into uncertainties in the results of said model [15]. It was assumed a Data Generating Process (DGP) that characterizes the population from which the simulated samples are drawn from sampling distributions of the economic losses according with different damage index. It was used a statistical analysis to infer characteristics of the DGP by analysing observable data sampled from the empirical distribution of the deterministic data [16].

2.2.3. Variance reduction in the context of Monte Carlo. Since the Monte-Carlo simulation can present a higher variance in the estimations, it was proposed a methodology with similar answer as our original one but with a lower variance, which is called variance reduction technique. The idea of variance reduction is replacing the original problem with another simulation problem, with the same results but smaller variance. There are many variance reduction techniques available such as antithetic method, control variates, moment matching method, stratified sampling, moment-matching, low discrepancy sequencing, Latin hypercube sampling, among others. One of the intuitively simplest and most widely used method is the method of antithetic and control variates [16].

The application of control variates involves employing a variable similar to that used in the simulation, but whose properties are known prior to the simulation. We employ as control variate the arithmetic average-cost per building of the Monte-Carlo simulation from deterministic distributions as
a controlled estimator in our simulation to reduce the variance of the economic losses according with different damage index.

2.3. Study Case
With the purpose to explain the proposed methodology, a case study located in one of the most landslide-prone zone of the city of Medellin-Colombia is analyzed, comparing different structural scenarios for a total of 48444 exposed buildings supplied by municipal Cadastral Office, which represents around 80% of all parcels in the study area. The study area is located in the northwest of Colombia, on the northeastern slope of the Aburrá Valley (AV), in the city of Medellin. Specifically, the area is centered on the coordinates 6° 15’ N, 75° 35’ W in the central part of AV as shown in figure 2. This area comprises three groups of neighborhoods (Popular, Santa Cruz and Manrique) with more than 400 000 inhabitants, settled in an area of 13.4 km². In general, slopes with gradients up to 30% and unplanned urbanization characterize the study area. Although the most frequent landslides are shallow and triggered by rainfall, deep-seated rotational landslides also occur with a lower frequency but with high impacts, triggered by groundwater flow from adjacent highlands of AV [8].

3. Results and discussions
From the hazard, vulnerability and cost results taken from [9], simulations were performed by the three methods described in section 2.2 for all scenarios. Figure 3 and Table 1 show the results obtained. As can be seen, the deterministic estimation [9] presents maximum values of US$200 million for scenarios 1 and 2, while the three probabilistic methods presented maximum values of on
the order of US$100 million. It is also observed that the deterministic estimation underestimates the losses for acceleration values lower than 0.4g.

As it is noticed, the results of the three probabilistic methods are approximately equal, but a greater efficiency in the calculation process is observed in the bootstrap simulation and Monte-Carlo simulation with reduction of variance methods because a less volatile scenario will be more favorable (with lower variance, it means, lower risk) since it allows better estimations, and therefore better predictions of economic losses in a landslide event, as they become less sensitive to small changes.

It is important to notice that the proposed simulations methodologies consider all possible building damage states while the deterministic methodology proposed by [9] only considers the economic losses if the damage index (DI) is higher than 50 %, then the obtained results can be better in the simulated scenarios. Besides, it is important to mention that between the simulated estimations the better results were obtained in the bootstrap simulation and Monte-Carlo simulation with reduction of variance, due to consider the possible economic losses with less variance, which can be traduced in less risk in the economic loss estimations.

It is important to highlight that under the probabilistic approaches, considering that all buildings in the study area fulfilled the requirements of the Colombian building code, NSR-10, evaluated as “Scenario 4”, the costs of a potential landslide would be reduced in an order of US$ 5 million approximately compared with the current structural condition evaluated as “Scenario 1” for the maximum expected horizontal acceleration in the city (Ah = 0.3 g). In fact, any kind of structural intervention has a relevant impact over economic losses, since it practically has a lower cost with respect to deterministic estimations. It can be seen that the structural interventions to reach the proposed and evaluated scenarios 2, 3 and 4, have an economic reduction of the order of 7%, 14% and 21% respectively, in comparison with the current structural condition of the exposed buildings, i.e. under the scenario 1.

| Ah  | S1  | S2  | S3  | S4  | S1  | S2  | S3  | S4  | S1  | S2  | S3  | S4  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.0 | 2.192 | 10.218 | 1.871 | 1.724 | 2.211 | 10.398 | 1.896 | 1.739 | 2.110 | 9.923 | 1.809 | 1.660 |
| 0.05| 3.412 | 2.046 | 2.912 | 2.680 | 3.456 | 2.060 | 2.950 | 2.719 | 3.299 | 1.966 | 2.815 | 2.594 |
| 0.1 | 5.188 | 3.180 | 4.430 | 4.074 | 5.267 | 3.219 | 4.527 | 4.165 | 5.026 | 3.072 | 4.320 | 3.975 |
| 0.2 | 10.981 | 4.833 | 9.382 | 8.619 | 11.172 | 4.902 | 9.531 | 8.780 | 10.661 | 4.678 | 9.095 | 8.379 |
| 0.3 | 20.399 | 18.970 | 17.436 | 16.008 | 20.737 | 19.299 | 17.820 | 16.316 | 19.789 | 18.417 | 17.006 | 15.571 |
| 0.4 | 33.507 | 31.145 | 28.649 | 26.287 | 34.106 | 31.736 | 29.324 | 26.841 | 32.548 | 30.286 | 27.984 | 25.614 |
| 0.5 | 49.448 | 45.953 | 42.288 | 38.794 | 50.344 | 46.837 | 43.301 | 39.633 | 48.044 | 44.697 | 41.323 | 37.822 |
| 0.7 | 80.423 | 74.821 | 68.785 | 63.184 | 81.771 | 76.204 | 70.437 | 64.693 | 78.034 | 72.722 | 67.218 | 61.737 |
| 1.0 | 108.045 | 100.784 | 92.384 | 85.122 | 109.485 | 102.721 | 93.536 | 87.292 | 104.482 | 98.027 | 89.261 | 83.302 |

Table 1. Results of statistical simulations for landslide risk assessment
4. Conclusions

The deterministic estimations tend to underestimate the losses due to events with short return periods. For this reason, the analyzed simulation methodologies provide a better estimation of economic losses for horizontal ground acceleration between 0 g and 0.3 g. Considering that the maximum expected horizontal acceleration (Ah) in the city is 0.3 g, these probabilistic approaches are very convenient for economic losses estimation purpose in the city.

This approach permits to establish urban planning guidelines in terms of the structural interventions to the exposed infrastructure to a potential disaster, because the municipal authorities and implicated stakeholders can determine a risk level acceptable and quantify the amount of investment to achieve it. In this study case, the proposed and evaluated scenarios 2, 3 and 4, have an economic reduction of the order of 7%, 14% and 21% respectively, in comparison with the current structural condition of the exposed buildings, i.e. under the scenario 1, with which it is possible to prioritize intervention zones and the public budget to achieve certain risk level considered as acceptable.

The results of the three probabilistic methods are approximately equal, having the bootstrap and Monte-Carlo simulation with reduction of variance better performance due to reduce the variance in the potential economic losses estimations, which it means a risk reduction in a potential landslide.
event. Also, since most of the data are obtained from secondary sources, our methodology is economical and provides a basis for decision-making in the planning of large areas and prioritize areas requiring further economic and technical studies.

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