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Landslide Risk: Economic Valuation in The North-Eastern Zone of Medellin City

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Landslide Risk: Economic Valuation in The North-Eastern Zone of Medellin City

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Abstract. Natural disasters of a geodynamic nature can cause enormous economic and human losses. The economic costs of a landslide disaster include relocation of communities and physical repair of urban infrastructure. However, when performing a quantitative risk analysis, generally, the indirect economic consequences of such an event are not taken into account. A probabilistic approach methodology that considers several scenarios of hazard and vulnerability to measure the magnitude of the landslide and to quantify the economic costs is proposed. With this approach, it is possible to carry out a quantitative evaluation of the risk by landslides, allowing the calculation of the economic losses before a potential disaster in an objective, standardized and reproducible way, taking into account the uncertainty of the building costs in the study zone. The possibility of comparing different scenarios facilitates the urban planning process, the optimization of interventions to reduce risk to acceptable levels and an assessment of economic losses according to the magnitude of the damage. For the development and explanation of the proposed methodology, a simple case study is presented, located in north-eastern zone of the city of Medellín. This area has particular geomorphological characteristics, and it is also characterized by the presence of several buildings in bad structural conditions. The proposed methodology permits to obtain an estimative of the probable economic losses by earthquake-induced landslides, taking into account the uncertainty of the building costs in the study zone. The obtained estimative shows that the structural intervention of the buildings produces a reduction the order of 21 % in the total landslide risk.

1. Introduction

In the last 40 years in the country, disasters have caused losses reaching US $ 7.1 billion, i.e. an average annual loss of US $ 177 million, and have been affected more than 1 million homes associated with the occurrence of different phenomena; 73 % by floods, 7 % by earthquakes, 5 % by landslides and 15 % by other phenomena. Between 1970 and 2011, 190000 homes were destroyed, of which about 18000 (9 %) were associated with landslides [1].

The Valley of Aburrá (VA) is located towards the northern part of the Colombian Andean Region (Figure 1) and corresponds to a topographic depression elongated in mountain area, where the city of Medellín and its neighbouring municipalities are located. In terms of relief, climate, topography, geology, among others, VA is a susceptible region to the occurrence of geomorphodynamic processes, which can affect both the population and its infrastructure [1]. In the VA, mass movements have caused considerable economic and human losses.
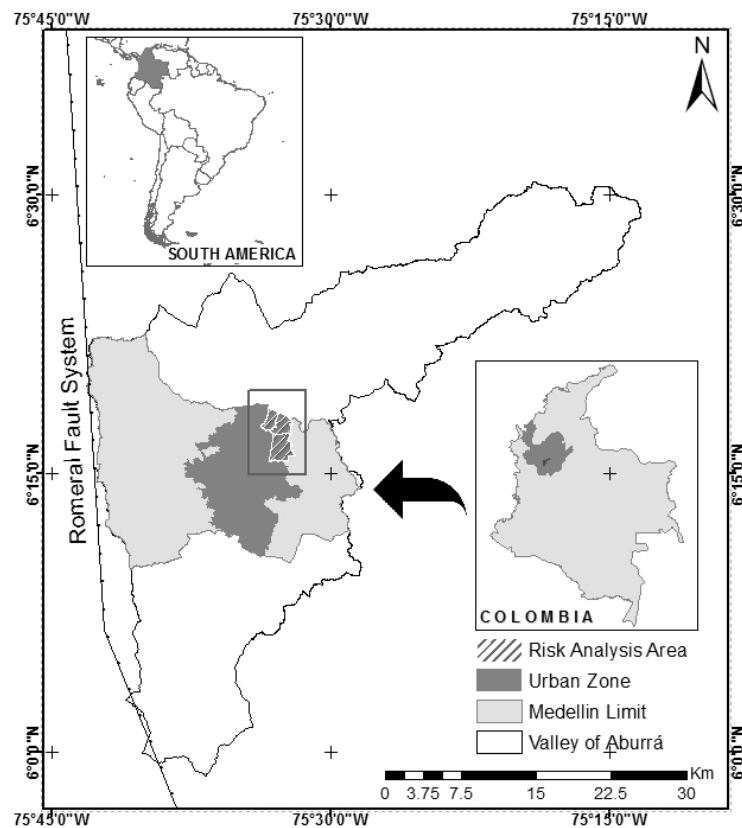
Figure 1. Location of VA and study area

Due to the occupation of the hillsides by human settlements and infrastructure, risks associated with mass movements have increased in recent years. It is estimated that in the VA, the 35 % of damage to buildings and 74 % of deaths due to natural phenomena, are associated with mass movements [2], while globally, such movements are attributed 0.53 % of deaths from disasters by natural phenomena [3].

For quantitative determination, the risk can be defined by the equation:

$$R = P[T] \times P[C/T] \times C \tag{1}$$

Where R is the risk, P[T] is the hazard understood as the total probability of a threatening event happens, P[C|T] is the vulnerability understood as the conditional probability of damage considering that a failure has already occurred and C is the cost of the consequences.

Currently there are methods that allow the probabilistic estimation of the hazard and vulnerability, but in terms of the costs of the consequences, their evaluation is usually of a deterministic type considering the cost of replacement of the exposed goods, which does not allow an adequate assessment of the uncertainty in this component. This paper presents an approach that considers the variability of costs or losses through a probabilistic model, combined with models of physical and probabilistic basis for estimating hazards by sliding triggered by earthquakes and rainfall, and a model for vulnerability that considers indices of structural fragility for buildings, calculated using decision trees. The final results are presented in a GIS application taking as a pilot area for risk estimation, a north-eastern zone of the city of Medellín, one of the areas most exposed to disasters in the municipality. In this paper, emphasis on the losses is made.

2. Methodology

A probabilistic methodology for risk assessment was developed using the methods as first order second method - FOSM, decision trees, and bootstrapping.

2.1. Hazard assessment

The methodology for the hazard assessment was developed by [4] and [5] based on FOSM. The methodology, shown graphically in Figure 1, allows to calculate the total probability of failure (TPF) according to the theorem of total probability of failure of a slope is given by the equation:

$$\text{TPF} = \text{P}[T] = P_{fs} \times P_s + P_{fns} \times (1 - P_s) \tag{2}$$

Where P_{fs} is the probability of slope failure due to the action of the earthquake in saturated condition, P_{fns} is the probability of failure where condition is not saturated, P_s is the marginal probability that the soil is saturated and $(1-P_s)$ is the marginal probability that the soil is not saturated. The probability of failure of the slopes in saturated and unsaturated condition can be calculated independently, but determine the probability that the soil is saturated is difficult due to the complexity of the phenomenon of variation of the conditions of soil water content. The effect of accumulated rainfall, and that the occurrence of landslides is possible relate to the amount of rainfall through so-called failure thresholds or numerical models with physical base to estimate the probability of saturation [6].

The probability of failure P_{fs} and P_{fns} are calculated by reliability index (β), as the probability that the factor of safety (FOS) is less than unity:

$$\beta = \frac{\text{E[FOS]} - 1}{\sigma[\text{FOS}]} \tag{3}$$

$$P_f = \Phi(-\beta) \tag{4}$$

Where E[FOS] the deterministic value of FOS is calculated with the mean values of the independent variables and σ[FOS] as the standard deviation of FOS, considering that the critical value of FOS is 1.0. Φ is the standardized normal probability distribution. The β index is related to the probability of failure, allowing a more consistent stability assessment.

The effect of earthquakes is calculated considering the Newmark's method based on a model of infinite slope stability. According to this method for the evaluation of stability by landslides triggered by earthquakes the force due to the earthquake is added to the model as a fraction of the weight of the sliding mass. Below the resulting expressions for infinite slope model to be used in this work are presented:

$$\text{FOS} = \frac{c}{\gamma H(\sin\alpha + A_h \cos\alpha)} + \frac{(\gamma H - \gamma_w H_w)\cos\alpha\tan\varphi}{\gamma H(\sin\alpha + A_h \cos\alpha)} \tag{5}$$

Where Ah is the acceleration due to the earthquake given as a multiple of the acceleration of gravity g, H is the thickness of the failure zone [m], H_w is the water height measured from the failure surface [m], c is the soil cohesion [kPa], φ is the angle of internal friction of the soil [º], γ is the unit weight of soil [kN/m3], γw is the unit weight of water [kN/m3].

In mountainous tropical regions, landslides occur most often in rainy seasons in which increased soil saturation with consequent decrease in their cohesion and increased pore pressure is presented. The process of decrease in the shear strength due to changes in water content is a highly complex process, which was not considered in the development of this study. Therefore, only the water pressure increase is taken into consideration in the assessment of soil saturation, and for purposes of analysis in

this study two situations were considered for the water height measured from the failure surface (H_w), one where the water level is presented in the most critical condition were considered i.e. $H_w=H$ to obtain P_{fs}, and another favourable in which $H_w=0$ to obtain P_{fns}. The eventual saturation condition of the soil is a random phenomenon that must be taken into consideration in the evaluation of the probability of landslides. In this case, it was considering the probability that the soil is saturated or not.

In this work, it is assumed that the probability of soil saturation P is related to the probability of the failure threshold being exceeded. This consideration of accepting that the condition given by the failure threshold represents a saturation condition conducive to landslides, with the already mentioned reduction of shear strength of the material due to the decrease in suction and pressure generation of pores [7], [1], [8]. After determining the probability that the soil was saturated according to data from climatological stations, a geostatistical interpolation process to estimate the probability of saturation in each of the cells was developed. The interpolation method used in this work corresponds to the method of Kriging.
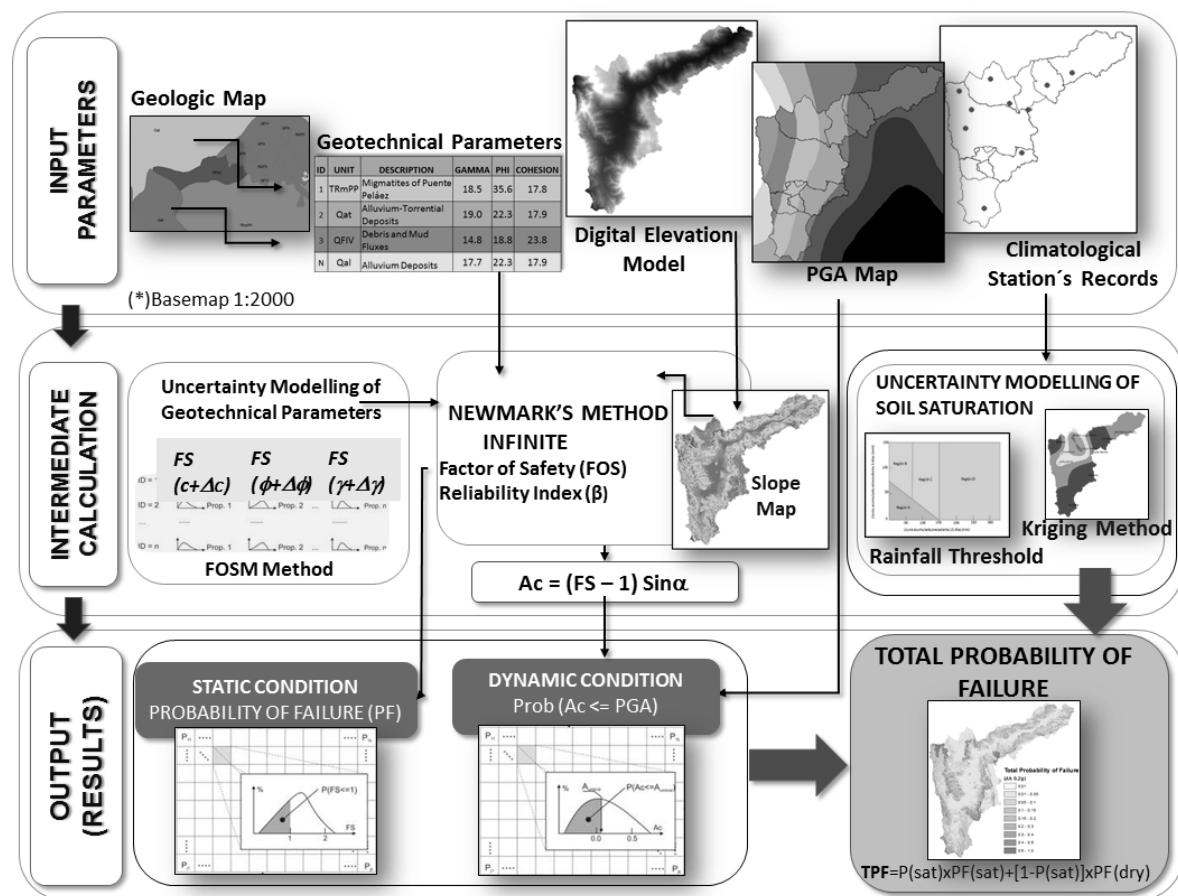

Figure 2. Schematic methodology adopted for hazard assessment

2.2. Vulnerability assessment

The physical vulnerability (PV) of a structure can be understood as the probability of damage when subjected to a particular effect of a natural or anthropogenic potentially damaging phenomenon, in this case a landslide. The assessment of vulnerability to this kind of hazard is a critical step within the risk analysis. The uncertainty is higher in the quantitative estimation of physical vulnerability to landslides due to the inherent subjectivity of the degree of loss associated with landslide magnitude [9]. The

physical vulnerability of a building can be defined quantitatively as a function of the intensity (I) of a landslide and the fragility (F) of the structural elements exposed to such movement, i.e.: PV=f(I,F). Intensity is associated with the destructive potential of the soil mass that slides, directly influenced by factors such as the speed of sliding soil mass, volume, kinetic energy, affected area, etc. Fragility is associated with the resistance of the exposed elements to ensure its functionality and physical integrity upon interaction exerted by the sliding soil mass.

In literature, different PV approaches can be found. Methodologies to assess the landslide impact in the infrastructure are based on: empirical relationships between landslide damages and its magnitude [10]; [11]; quantification of vulnerability based on expert knowledge [12]; quantitative estimation of vulnerability based on scenarios considering different kinematic intensity models [13]; and structural fragility indexes, as well as the definition of damage level of buildings via decision trees [5].

The fragility of buildings is associated with the resistance of structural elements to ensure its functionality and physical integrity against the force generated by the sliding soil mass. The physical characteristics of each building must be considered to classify them in different categories according to their structural response. Cadastral database analysis of buildings is useful for this, because it is possible to determine the type of structural system, condition, number of floors, building age and type of cover (ceiling). This classification is determined from decision trees that consider the level of damage to each building based on the combination of their different physical characteristics, allowing rank them according to expected structural response for each category. The building classification system used in this proposal has been adopted from [14].

In this paper, vulnerability is assessed by using the methodology proposed by [5] and summarized in Figure 3. It considers the definition of damage level to buildings with a calculated index using decision trees. This index is based on the rating of the five aforementioned factors which are obtained from cadastral records, once the building has been classified according to its structural response. These attributes are related to the fragility of the structural system of the buildings to meet the demands in case of a seismic event or a landslide, which reflects the interaction between the type of structure and some of its characteristics. The basic data source for the aforementioned attributes can be the municipal Cadastre Office database. This data is processed to obtain a registration for each building depending on its use and the type of housing and building materials. Then the database is processed and refined to obtain a unique index that groups the least favourable conditions of each attribute. This is done from the vulnerability point of view for each building, considering a scenario where constructions are settled directly on a sliding block or soil mass.

In order to estimate the vulnerability index of households, it was necessary to acquire a cartographic database of 48444 relevant properties (parcels) located in the north-eastern zone of the city of Medellín, which represents around 80 % of all parcels in the study area. A text file with appropriate alphanumeric information on the structural characteristics of each property was obtained, and it was possible to create a single spatial database. Attributes of the structural system of buildings were used, including age of construction, structural condition, number of floors, type of structural system and type of roof (ceiling), provided by [15].

Along with these decision trees, a vulnerability index is estimated for each type of building material in the main structure. It allows assigning a value to each variable and to all the combinations in order to reach a final value indicating the level of brittleness and susceptibility to damage of each building. This approach indicates that the lowest value (1) corresponds to the best condition and the highest value (5) corresponds to the worst condition in the least favourable scenario. For example, a two-level masonry structure, with less than ten years of age and in good maintenance condition would have a vulnerability index of 1.0. In the case of brick and concrete structural systems with a cover of

concrete slab, we have a decrease of 0.5 in the value of the physical vulnerability indicator, obtaining a final result of 0.5 for this indicator. Therefore, since the diaphragm effect generated by the slab contributed to the rigidity of the structure, it reduced to some extent its fragility or susceptibility to damage. This was taken into account for the structural systems already mentioned, as well as for those with the capacity to support the weight of that type of cover. Once completed, this index was normalized to obtain the normalized vulnerability index (NVI) values ranging from zero to one so that it would be compatible with the range used in hazard.

Two structural scenarios were considered in the analysis of vulnerability. The first one (S1), corresponds to the current structural condition, and the last one (S2), involves a structural type of supporting walls with stiffening elements, which fulfils the minimum structural requirements of Colombian building code (NSR-10) [16]. Thus, it is possible to analyse the effect of a structural intervention in the buildings, allowing a better response to the stresses generated by the sliding soil mass.

Once the normalization process of vulnerability index is made, and all structural scenarios are considered, it is possible to display the results in graphic way in form of maps which indicate the fragility of the structural system of buildings.
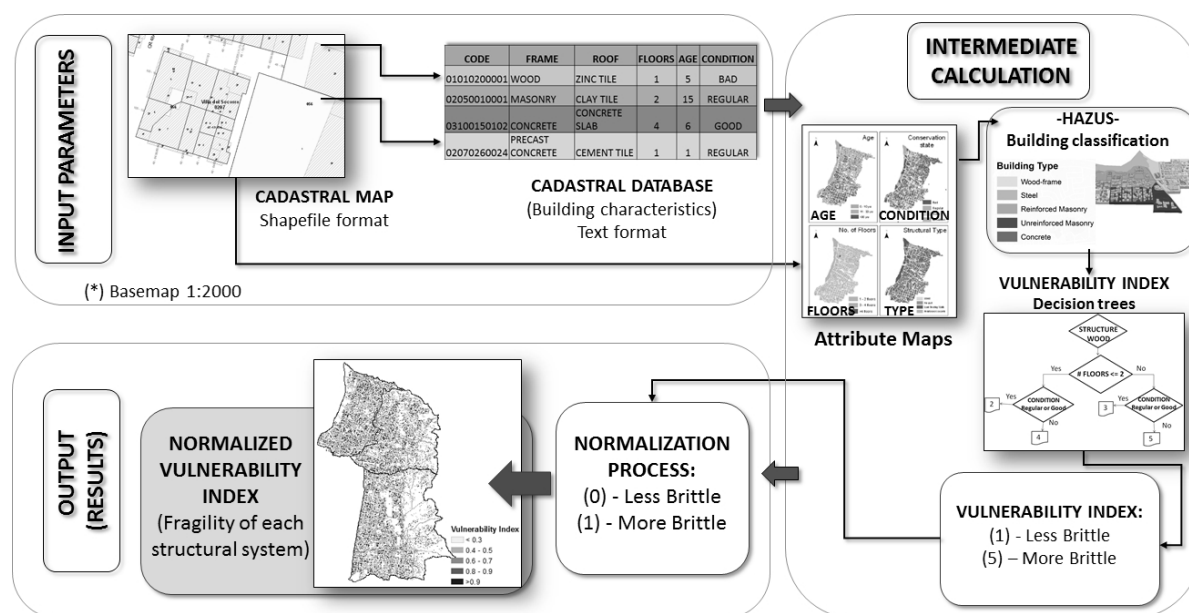

Figure 3. Schematic methodology adopted for vulnerability assessment

2.3. Economic Value (C) and Damage Index (DI) assessment

The bootstrap simulations of statistical models are commonly used to characterize empirical landslide parameters distributions (see for example [17]; [18]; [19] and [20]). The bootstrap is a data-based simulation method for statistical inference. It is a conventional stochastic simulation (as Monte Carlo, Markov and Gaussian processes, among others), 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 [21].

The implemented probabilistic approach considers several scenarios of damage and vulnerability to measure the magnitude of the landslide and to quantify the economic costs. This research compares different risk scenarios using the bootstrap to obtain estimates of the confidence intervals. For this purpose, a computer routine was developed in the software R Project, using like input parameters the building cadastral values and the damage indexes (calculated like the product of TPF and NVI), for each one of 48444 analysed buildings. In total, 1000 bootstrap samples were generated with corresponding 95 % confidence intervals. It was used 1000 independently drawn bootstrap replications in order to estimate the economic value (C) and the damage index (DI) for different risk scenarios. Test samples are generated by drawing, with replacement. In Figure 4, methodology adopted for risk assessment can be analysed.

Bootstrap confidence intervals, which use more of the information in the bootstrap histogram than just its standard deviation. [21]. Then, the bootstrap histogram strongly resembles the population histogram.
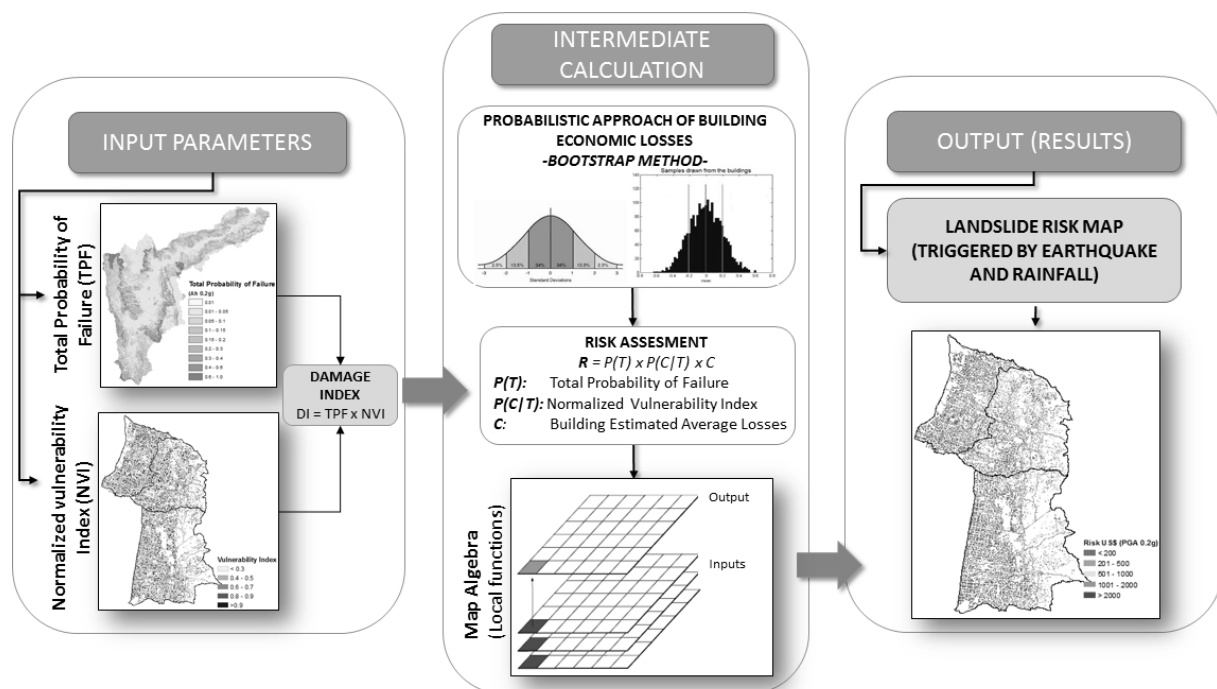

Figure 4. Schematic methodology adopted for risk assessment

3. Results and discussions

Table 1 summarizes the results of bootstrap simulation for two scenarios: The first one (S1), represents the current structural condition, and the last one (S2), considers an assumed scenario with a structural type of supporting walls with stiffening elements, which fulfils the minimum structural requirements of Colombian building code. For each analysed structural scenario nine different earthquake horizontal accelerations (Ah) were considered.

For each bootstrap iteration, the algorithm drew the same number of observations within each primary sampling unit as were present in the original sample. We find that the 95 % confidence intervals on the estimated EV with total losses are US$7504.14 to US$7848.59. The 95 % confidence intervals for the partial losses are: 75 % losses from US$5628.11 to US$5886.44; 50 % losses from US$3752.07 to US$3924.30 and 25 % losses from US$1876.04 to US$1962.15. The total loss represents the estimated losses for all building damage states and each horizontal acceleration.

Table 1. 95% Confidence intervals for total losses per building

Variable		Mean [a]		Variance		Standard deviation [a]	
Scenario	Ah	Lower	Upper	Lower	Upper	Lower	Upper
EV		7504.14	7848.59	18831.50	19075.06	60.49	61.28
S1	0	44.64	45.89	68.17	69.05	0.21	0.22
	0.05	69.59	71.26	91.06	92.24	0.292	0.296
	0.1	106.00	108.19	119.39	120.94	0.383	0.388
	0.2	224.89	228.49	196.38	198.92	0.630	0.639
	0.3	418.32	423.87	303.68	307.60	0.975	0.988
	0.4	687.69	695.66	435.45	441.08	1.398	1.417
	0.5	1015.32	1026.13	590.43	598.07	1.896	1.921
	0.7	1652.82	1667.43	798.66	808.99	2.565	2.599
	1.0	2222.40	2238.24	865.80	877.00	2.781	2.817
S2	0	35.05	36.11	58.46	59.22	0.188	0.190
	0.05	54.61	56.05	78.65	79.66	0.252	0.255
	0.1	83.15	85.05	104.09	105.44	0.334	0.339
	0.2	176.31	179.52	175.32	177.58	0.563	0.571
	0.3	327.89	332.98	278.14	281.74	0.893	0.905
	0.4	538.89	546.37	408.44	413.72	1.312	1.329
	0.5	795.64	805.95	563.99	571.29	1.812	1.835
	0.7	1296.91	1311.61	803.37	813.76	2.581	2.614
	1.0	1748.50	1765.76	943.62	955.82	3.032	3.070

[a] Values in US$ Dollars

Figure 5 shows the obtained results for two evaluated scenarios, which are compared with deterministic assessments made for the same scenarios by [5] using decision trees. It is observed that for horizontal acceleration values less than 0.3g (maximum horizontal acceleration of the ground expected for this zone, according to a 2002 study of seismic microzonation for Medellín City), the expected losses are higher than expected losses obtained by deterministic way, while for horizontal acceleration higher than 0.3g, lower estimated losses are obtained.

It is important to notice that the proposed methodology considers all possible building damage states while the deterministic methodology only considers the economic losses if the damage index is higher than 50 %. For this reason, the bootstrapping provides a better estimation of economic losses for horizontal acceleration between 0g and 0.3g which are the most probable earthquakes in the region, and correspond to earthquakes with a 250-year return period.

Also, it can be observed in the Figure 5 that the total economic losses curves of evaluated scenarios using the proposed methodology present a gradual variation with a lower discrepancy in higher accelerations, in contrast with deterministic method that shows a very marked difference. It was found that under an assumed scenario in which all the constructions in the study area fulfil the requirements of the Colombian building code (NSR-10) [16], there is a decrease in costs arising from the effect of disaster landslides of approximately 21 %. This is compared to the condition of the actual structural scenario for the maximum horizontal ground acceleration expected in the city, which is an earthquake with a 475- year return period according to a 2002 seismic microzonation study. It is noted that the improvement of the structural quality of buildings has a major effect on estimated damage costs; even without the full implementation of the NSR-10, these costs may decrease between US$0.5 and US$22 million depending on the period of earthquake recurrence.
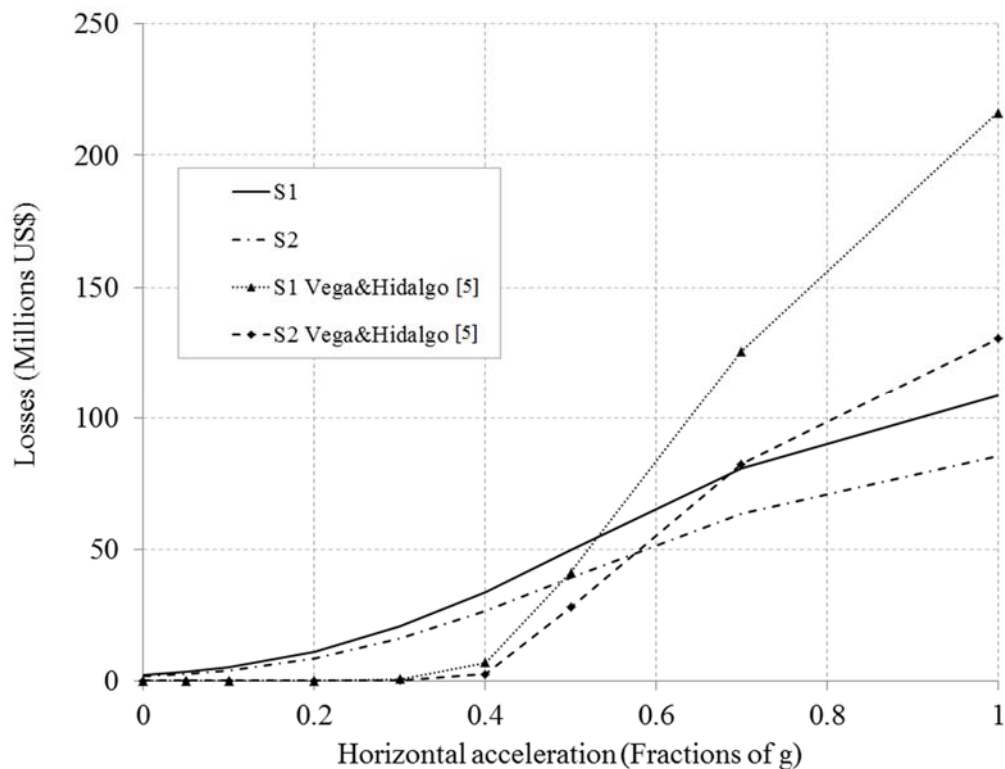
Figure 5. Total losses per building of a potential landslide triggered by earthquake in study zone

4. Conclusions

The proposed methodology permits to obtain an estimative of the probable economic losses by earthquake-induced landslides, taking into account the uncertainty of the building costs in the study zone. Since most of the data are obtained from secondary sources, the methodology is economical and provides a basis for decision-making in the planning of large areas and prioritize areas requiring further study. This fact allows to evaluate different seismic and structural scenarios in an economical way and provides basis for decision-making in the planning of large areas and prioritize areas requiring further study.

The obtained estimative shows that the structural intervention of the buildings produces a reduction of approximately 21 % in the total landslide risk. Hence, considering that through this structural actualization the risk is decreased, it is convenient generate this kind of intervention for urban planning of informal settlements.

In contrast with deterministic methods, estimated values with proposed methodology tend to sub estimate the potential economic losses for earthquake with high return periods and low occurrence probability because in this case all possible building damage states are considered while the deterministic methodology only considers the economic losses if the damage index is higher than 50 %. For this reason, this method provides a better estimation of economic losses for horizontal acceleration between 0g and 0.3g.

References

[1] J. A. Vega, Risk Estimate by Landslides Generated by Seismic Events in Medellin Using Tools of Geomatics. Application to urban buildings, La Plata: Engineering Astronomical and Geophysical Sciences, National University of La Plata, 2013, p. 51.

[2] P. A. Isaza-Restrepo, H. E. Martinez and C. A. Hidalgo, "Methodology for quantitative landslide

risk analysis in residential projects," *Habitat International,* vol. 53, pp. 403-412, April 2016.

[3] R. Chowdhury, P. Flentje and G. Bhattacharya, Geotechnical Slope Analysis, London: Taylor & Francis, 2010, p. 737.

[4] C. Hidalgo and J. A. Vega, "Hazard estimation for landslides triggered by earthquakes and rainfall (aburrá valley-colombia) (Spanish)," *Revista EIA,* vol. 11, no. 22, pp. 103-117, 2014.

[5] J. A. Vega and C. A. Hidalgo, "Quantitative risk assessment of landslides triggered by earthquakes and rainfall based on direct costs of urban buildings," *Geomorphology ,* vol. 273, p. 217–235, 2016.

[6] M. Parra, Model for the study of the threat of mass movements detonated by rains in the Llanaditas neighborhood of the city of Medellín (Spanish), Medellín: Universidad Nacional de Colombia, 2015, p. 80.

[7] C. A. Hidalgo, J. A. Vega, A. P. Assis and M. R. Villarraga, "Estimation of landslides hazard in linear projects: roads in residual soils (Spanish)," in *Proceedings of IV Panamerican Simposium on Landslides*, Paipa, 2012.

[8] C. A. Hidalgo, Uncertainty, Vulnerability and Risk Assessment Due to landslide on Roads (Portuguese), Brasilia: Department of Civil and Environmental Engineering, University of Brasilia, 2013, p. 250.

[9] M. Silva and S. Pereira, "Assessment of physical vulnerability and potential losses of buildings due to shallow slides," *Nat Hazards,* vol. 72, p. 1029–1050, 2014.

[10] F. Leone, J. P. Asté and E. Leroi, "Vulnerability assessment of elements exposed to mass movements: working toward a better risk perception," in *Landslides-Glissements de Terrain*, Rotterdam, 1996, p. 263–270.

[11] M. Papathoma-Kohle, A. Zischg, S. Fuchs, T. Glade and M. Keiler, "Loss estimation for landslides in mountain areas - An integrated toolbox for vulnerability assessment and damage documentation," *Environmental Modelling & Software,* no. 63, pp. 156-169, 2015.

[12] . J. Zêrere, R. García , S. Oliveira and E. Reis , "Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal)," *Geomorphology,* no. 94, p. 467–495, 2008.

[13] M. Uzielli, F. Nadim, S. Lacasse and A. Kaynia, "A conceptual framework for quantitative estimation of physical vulnerability to landslides," *Eng. Geol,* vol. 102, p. 251–256, 2008.

[14] HAZUS, "Multi-hazard loss estimation methodology earthquake model," Jessup, Maryland, 2003.

[15] Municipal Cadastral Office of Medellín, "Cadastral Inventory Geodatabase," Medellín, 2014.

[16] Association of Earthquake Engineering, "Colombian Code for Earthquake-resistant Construction NSR-10 (Spanish)," 2010.

[17] O. G. T. &. H. Y. Korup, "Without power? Landslide inventories in the face of climate change," *Earth Surface Processes and Landforms, 37 (1),* pp. 92-99, 2012.

[18] J. N. G. R. H. &. B. A. Goetz, "Integrating physical and empirical landslide susceptibility models using generalized additive models," *Geomorphology, 129(3),* pp. 376-386, 2011.

[19] D. T. P. B. R. I. &. C. T. T. Bui, "A Comparative Assessment Between the Application of Fuzzy Unordered Rules Induction Algorithm and J48 Decision Tree Models in Spatial Prediction of Shallow Landslides at Lang Son City, Vietnam," *Remote Sensing Applications in Environmental Research,* pp. 87-111, 2014.

[20] X. R. D. G. W. C. J. X. Q. &. G. T. Fan, "Empirical prediction of coseismic landslide dam formation," *Earth Surface Processes and Landforms, 39(14),* pp. 1913-1926, 2014.

[21] B. T. R. Efron, An Introduction to the Bootstrap, Chapman and Hall, 1993.

[22] T. L. J. B. &. C. M. Park, "Confidence intervals for evaluating benefits estimates from

dichotomous choice contingent valuation studies," *Land economics, 67(1),* pp. 64-73, 1991.