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Physical Vulnerability Index before the Landsliding Hazard in Houses Located in the Locality of Rafael Uribe Uribe, Bogotá D.C.

Índice de Vulnerabilidad Física ante la Amenaza de Deslizamiento de Suelos en Viviendas Ubicadas la Localidad de Rafael Uribe Uribe Bogotá D.C.

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ABSTRACT. The present work carried out an analysis study of the physical vulnerability index for the hazard of landslide for the Rafael Uribe Uribe locality in Bogotá DC, using the Leona methodology with historical data of mass removal between the years 2008 to 2015, with a registry of 454 events, of which 426 are considered, given that the rest corresponds to rock falls, which may also affect general vulnerability, the methodology used does not apply. Technical concepts have been designed for the competent entities in the sectors that have presented the phenomenon of the mass removal in Rafael Uribe Uribe and the existing technical sheets for each of them, as well as the delimitation of each of the polygons, was carried out on a local map with 31 polygons that historically have presented a phenomenon of mass removal. The physical vulnerability index of the elements exposed to the situation of the events that can be classified as deformations or lateral displacements, which can be classified as moderate, is adjusted, however, the periods of rain, the solicitations may present deformations very fast.

keywords: Physical Vulnerability Index, Landslide, Leone Methodology.

RESUMEN. El presente trabajo realizó un estudio del índice de vulnerabilidad física para la amenaza de deslizamiento de suelos para la localidad Rafael Uribe Uribe en Bogotá D.C., utilizando la metodología Leone con datos históricos de remoción en masa entre los años 2008 al 2015, con un registro de 454 eventos, de los cuales se consideraron 426, dado que el resto corresponde a caídas de rocas, que aunque también pueden generar vulnerabilidad física, no aplica la metodología utilizada. Se consideró conceptos técnicos generados por la entidades competentes en los sectores que han presentado fenómeno de remoción en masa en la localidad de Rafael Uribe Uribe y las Fichas técnicas existentes para cada uno de ellos, así como la delimitación de cada polígono, se realizó un mapa local con 31 polígonos que históricamente han presentado fenómeno de remoción en masa. Se estableció el índice de vulnerabilidad física de los elementos expuestos considerando la magnitud de los eventos (solicitación) que corresponde a deformaciones o desplazamientos laterales, que se pueden catalogar como moderados, sin embargo en los periodos de lluvias, las solicitaciones pueden presentar deformaciones muy rápidas.

Palabras clave: Indice de Vulnerabilidad física, Deslizamiento de Suelos, Metodología Leone.

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1 | INTRODUCTION

Bogotá's urban growth has implied a higher demand on housing, utilities, road infrastructure and social assistance in recent decades [1]. This represents a social pressure on the ecologic structure of the city, since the urbanization in hillside areas, mostly have been developed without any planning, but motivated by the families' need to obtain housing in sectors dedicated to extraction of construction materials and, without the approval of the competent authority, promoting a progressive environmental deterioration, altering the stability conditions in the hillsides and zones with presence of mass removal phenomena, such as landslides, mud flows and rock downfalls.

The causes of mass removal phenomena in the Rafael Uribe Uribe locality are directly associated to water infiltration that generate the washing of soil fine material, causing landslides that generate damage to estate and that generate physical vulnerability for the people that live there [2]. Relating the intensity of the mass that can be displaced with the fragility of exposed elements, one can stablish damage levels for each building, and based on this damage levels, physical vulnerability categories are defined such as they give input to the vulnerability zoning map [3].

The Rafael Uribe Uribe locality has a total aera of 820,82 ha in zones threatened mass removal, where 1412 blocks are located. From that total, there are 191 blocks that occupy an area of 123.2 ha, classified as high risk removal zones; additionally 1104 blocks occupying 461.3 ha are classified as medium risk removal zones, and 117 blocks in a 236.3 ha area that are classified as low risk removal zones [4].

According to the population projections reported up to 2017, in the locality of Rafael Uribe Uribe, it is considered that the Zonal Planning Units (UPZ) where mass removal phenomena is present are No. 53 Marco Fidel Suárez with population of 60885, No. 54 Marruecos 91748 inhabitants, and No. 55 Diana Turbay with 70322 inhabitants, which is the most vulnerable population, exposed directly or indirectly to this hazard [5].

Geomorphology is constituted by the La Regadera sandstones sector: formed with quartz, slightly resistant ferruginous cement sands; corresponding to zones of strongly inclined topography. The clayey friable sandstones sector: low to medium resistance, from the lower and superior floors of Usme's formation; here the sandstones underground exploits are located. However, in natural conditions, this rocks present good stability, a high humidity content makes them lose completely their cohesion and shear resistance, reason why the urbanization of such areas requires the previous elimination of sand extractors, specially those underground, located in the neighborhoods of Villa Gladys, Bochica, Marco Fidel Suárez and Marruecos [4].

The risk for mass removal in the Rafael Uribe Uribe locality has a dynamic factor without urban growth planning. Producing emergency situations from the mass removal hazard and the present fragility in the housing construction for the community; events that have been attended by the Emergency Attention and Rescue organisms in Bogotá.

2 | MATERIAL AND METHODS

In the development for the methodology a base line was considered with the technical information for each of the 31 polygons and applying the Leone methodology, as shown on Fig. 1. The base line was considered starting from 2008, with data generated by the corresponding public entities, such as the District Institute for Risk Management (IDIGER), the Rafael Uribe Uribe Local Mayor's office, and the official fire department. Table 1 shows the consolidated compiled secondary data.

Events by mass removal phenomena in the Rafael Uribe Uribe locality have coincided with climate phenomena that produce the increase in precipitations according to technical studies from the Institute for Hydrology, Meteorology and Environmental Studies (IDEAM), institution responsible for the surveillance of the national climate system. In 2009 and first semester of 2010, El Niño phenomenon was present, and produced a significant decrease in rains. For the second semester of 2010, 2011 and up to the first semester of 2012, la Niña produced the increase in precipitations, coinciding with the increase in mass removal events in the locality.

In Fig. 2 is evidenced an increase in the mass removal events with the precipitation increase produced by La Niña phenomenon. Starting from the secondary data obtained from the 29 technical sheets corresponding

to the polygons declared in Risk by Mass Removal in the Rafael Uribe Uribe locality, whose registers are of official character from the Prevention and Emergency Attention Fund (FOPAE) between 2011 and 2012, these were concerted and approved by the Local Council for Emergency (CLE). With this data we present a local map with 31 polygons and the historical mass removal events [6] (Fig. 3).

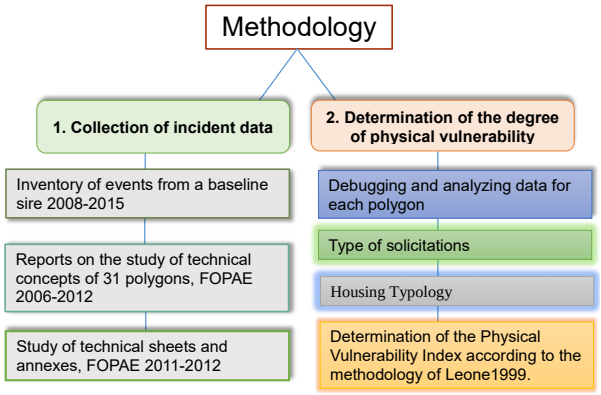

FIG. 1 Methodologic framework.

FIG. 2 Average of the annual pluvial precipitation Vs Number of mass removal events in the studied area. Data taken from IDIGER 2016 [6].

However, Fig. 3 does not include zones that has a use restriction by urban regulations, because they are grounds with protection for landslide hazard, such as the case of the Nueva Esperanza sector, which was attached to the Mountain District Park Entrenubes, where 1205 family nuclei were relocated, and the Socorro sector, where mining exploits were performed until 20 years ago and where the brickworks were located, and in consequence, the ground is unstable [4].

The reading of registered information in the technical sheets indicate that is necessary an update of the map for the risk of mass removal zones from the District Secretary of Planning and the IDEGER (Previously FOPAE) in some polygons catalogued and delimited as low or medium risk zones, since they do not correspond to the risk level given the high number of mass removal events presented in latter years, specifically in those with the most pluvial precipitation levels (2010, 2011 and 2012) and the number of affected families and with a great number of relocations, such as Los Puentes, Diana Turbay Cultivos, Rincón del Valle, Bosques de San Carlos, La Merced, La Arbolera and Colinas neighborhoods. Is important to include the previous information in the map of historic events for mass removal for the locality, according to events registered in the technical sheets for each of the polygons and the number of landslide incidents reported in latter years by the SIRE [7].

2.1 | Determination of the Vulnerability Index

Based on the technical concepts reported by IDIGER and the local mayor's office, in the ZPU 55 Diana Turbay is located the largest quantity of families included in the resettlement program, where a considerable amount of processes of mass removal have materialized by different factors, followed by the ZPU 53 Marco Fidel Suárez and 54 Marruecos with a lower proportion of identified properties with High non mitigable risk [6][8].

TABLE 1 Annual report of events caused by mass removal phenomena in the Rafael Uribe Uribe locality [7].

Year	2008	2009	2010	2011	2012	2013	2014	2015	Total
Total Events per Mass Removal	20	10	53	252	86	12	11	10	454

With respect to the evaluation of physical vulnerability for the landslide hazard, three types of models have been considered: qualitative, semiquantitative and quantitative [9], [10]. Applying the Leone (1999) methodology, which classifies housing within five groups of typology and proposes values for damage with

respect to the exposition of different requests. In Fig. 4, two zones are distinguished, an upper zone (in the body of the landslide) or direct influence zone, the damages that the houses could suffer can be related to lateral displacements (LD) that, also, depend on the velocity of the movement (the faster the movement, the greater the damage).

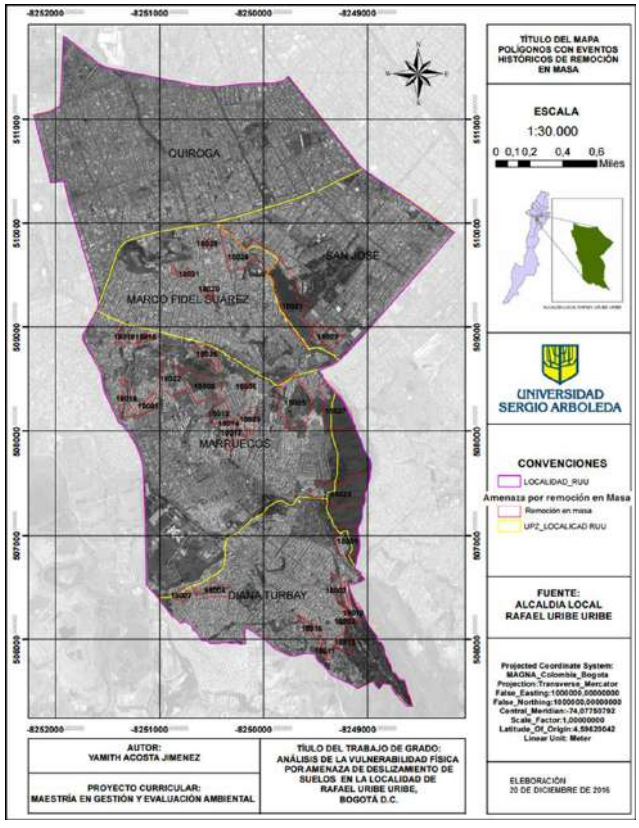

FIG. 3 Map of historic events for mass removal with secondary data reported by the corresponding authorities (By Authors).

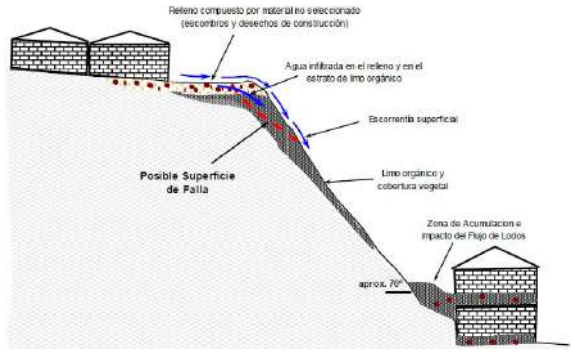

FIG. 4 Schematic for a landslide [8]

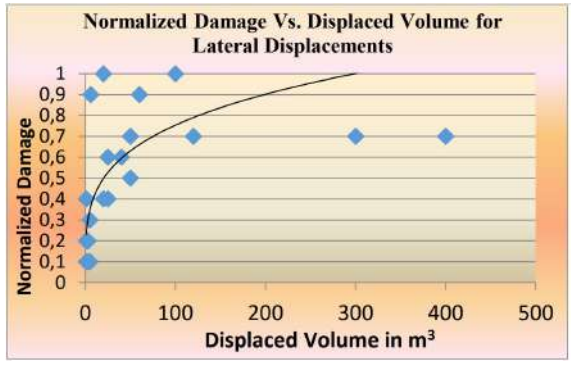

FIG. 5 Relation between normalized damage and displaced volume in lateral displacements.

For the movement velocity characterization, the scale proposed by Cruden and Varnes, consigned in Table 3 [11]. In the lower zone (below the body of the landslide) or Indirect Influence zone, the damages in the houses can be related to the lateral pressures (LP) that, likewise, can be associated with height achieved by material accumulation against the building, as shown on Table 2.

TABLE 2 Categories for lateral pressures

Description	Class	Characteristics
High lateral pressure	PL 1	Greater than 2/3 of the building's height
Medium lateral pressure	PL 2	Between 1/3 and 2/3 of the building's height
Low lateral pressure	PL 3	Lesser than 1/3 of the building's height

For the case in study, the magnitude of the event (request) corresponds to moderate deformations on the lateral displacements, that can be catalogued as moderate (VM3), however, during rain periods, the requests generally correspond to very fast deformations, greater than 50mm/s. On the other side, housing located in the low part, requests (PL2) are for medium lateral pressures [11]. Vulnerability: On determining the vulnerability for the buildings against landslides, the calculus known as Physical Vulnerability Index (PVI) is employed, as well

as the methodology proposed by Leone [12], and modified by Soler [13]. The work consists on calculating the physical vulnerability indexes, depending on the type of movement, intensity of requests and characteristics on the exposed element (houses).

TABLE 3 Velocity ranges for a landslide

Description	Clase	Velocidad características
Very Fast	VM1	Greater than 50 mm/s
Fast	VM2	Between 0.5 mm/s and 50 mm/s
Moderate	VM3	Between 0.05 mm/s and 0.5 mm/s
Slow	VM4	Between 0.005 mm/s and 0.05mm/s
Very Slow	VM5	Lesser than 0.005 mm/s.

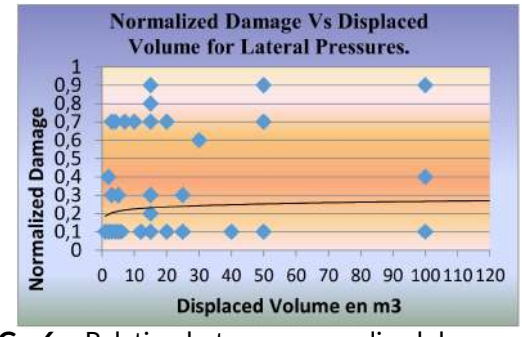

FIG. 6 Relation between normalized damage and displaced volume for lateral pressures.

TABLE 4 Structure resistance criteria

Request Type	Damage modes	Structure resistance criterio
Lateral Displacements	Transport. Deformation. Settlement. Rupture.	Ground foundation depth. Structure drag.
Lateral pressures	Deformation. Rupture.	Structure height. Ground foundation depth.

Leone's methodology is oriented to evaluating the physical vulnerability in order to quantitatively estimating the risk, for which the exposed elements are reduced to two groups: physical goods and people's integrity. Characterization of exposed elements: Starting from the primary information consulted in the diagnostics for each polygon, as well as the technical sheets, the characterization for the conditions of the ground and hillsides and delimiting each polygon, we will carry out the phase on characterizing the exposed elements. Each identified and located element must be described and categorized in function of their characteristics such as typology, exposition and fragility (Table 4).

TABLE 5 Classification for housing typology

Building type	Description
B1	Houses built of recycled material.
B2	House in masonry without structure.
B2	Prefabricated House.
B3	Buildings of up to two (2) levels of Good quality construction (with structure).
B4	Buildings of over two (2) levels of good quality construction (with structural reinforcement).

Structure typification: In general, physical vulnerability is a function both of the phenomena intensity as well as the resistance of the exposed element. Houses are typified considering the criteria for structure resistance according to the previously exposed criteria, for typifying housing we adopt the Leone criteria, summed up in Table 5. Predominant houses in the studied polygons correspond to types B1 Houses build of recycled material and B2 Houses in masonry. Damage qualification: In the methodology proposed by Leone, in order to qualify the damage produced in the houses by mass removal phenomena, we follow the DRM (Délégation aux Risques Majeurs) criteria [14], which divides damages in five (5) categories.

TABLE 6 Classification of damages according to the DRM.

Damage Index	Damage type	Damage percentage
I	Light non-structural damage.	0.0 - 0.1
II	Walls cracking. Fissures.	0.2 - 0.3
III	Significant deformations.	0.4 - 0.6
IV	Structure fracture.	0.7 - 0.8
V	Partial or Total collapse.	0.9 - 1.0

TABLE 7 Methodologic framework.

VULNERABILITY CATEGORY	CRITERIA
HIGH	Average IVF $\geq$ 0.65
MEDIUM	0.35 $\leq$ Average IVF < 0.65
LOW	Average IVF < 0.35

The damage normalized value was compared with the volume of slipped material, in order to identify the relation between the landslide magnitude measure and the damage caused by the landslide on the exposed houses (Figs. 5 and 6). These representations are known as fragility, vulnerability or damage curves, with which one can determine from hazard conditions the physical risk indexes by mass removal phenomena. Starting from the technical sheets on the 31 polygons in the Rafael Uribe Uribe locality that had presented a mass removal phenomena, we were able to identify the existence of a relation between the type and magnitude of the landslide with the damage in structures. Although is not a uniform trend, in Figs. 5 and 6 a line is traced which could represent a trend, more clearly shown in Fig. 5, which represents the levels of damage generated by lateral displacements. Even though these are present with less frequency than the lateral pressures, still can induce greater damage in the structures.

TABLE 8 Damage matrix for structures or houses

	Event magnitude or class	B1	B2	B3	B4
		Building typology			
Lateral displacement	VM1 > 50mm/s	V	V	V	IV
	VM2 $\in [0.5, 50]$ mm/s	V	V	IV	IV
	VM3 $\in [0.05, 0.5]$ mm/s	V	IV	III	III
	VM4 $\in [0.005, 0.05]$ mm/s	IV	III	III	II
	VM5 < 0.005 mm/s	III	II	I	I
Lateral force	PL1 > 2h/3 with h:=housing height	V	IV	III	III
	PL2 $\in [h/3, 2h/3]$	V	IV	III	II
	PL3 < $h/3$	IV	III	II	I

Based in the presented results for the vulnerability analysis, categorizing the value for Physical Vulnerability Index (PVI) according to the criteria stablished in studies for Bogotá D.C. by F. Soler, A.J. González [12] et. al. These are presented in Table 7. In order to determine the physical vulnerability index, we considered the data presented in the Technical diagnostics and datasheets, where they describe the ground and hillside conditions, type of request presented and characteristics for the houses. Using the historic information for the locality, we calculate the damage index and the degree of physical vulnerability in the affected polygons by the mass removal phenomena (landslides) in the locality of Rafael Uribe Uribe, as shown in Table 9. Damage Matrix: Is associated to Potential Damage Indexes (PDI) caused by a given event, according to both the request type (event magnitude) as well as the house typology (resistance to exposed element). We present the damage matrix used in Table 8. According to Table 8 and the detailed cases, we obtained that for 19 polygons the vulnerability is high, mainly where predominates the housing types B1 and B2, the requests that produce the most severe effects are lateral landslides, more than lateral pressures. Lateral pressures generate a medium vulnerability degree, since the predominant type of house in such sectors (B2), mostly can withstand the amount of material that falls on them.

TABLE 9 Estimate for the degree of physical vulnerability in the polygons declared as threatened by mass removal phenomena in the locality of Rafael Uribe Uribe

No.	Polygon	Request Type	Building Typology	Damage Index	Physical Vulnerability
1	Playón Playita	VM1	B2	V	High
		PL3	B2	III	Medium
2	Molinos De La Caracas	N/A	N/A	N/A	N/A
		PL3	B4	I	Low
3	La Merced Sur	VM1	B2	V	High
		PL3	B2	III	Medium
4	La Marquesa	VM1	B2	V	High
		N/A	N/A	N/A	N/A
5	San Ignacio - Villa Neiza	N/A	N/A	N/A	N/A
		PL3	B3	III	Medium
6	Diana Turbay Sector Cultivos I	N/A	N/A	N/A	N/A
		PL3	B3	II	Low
7	Rincón Del Valle	N/A	N/A	N/A	N/A
		PL2	B2	III	Medium
8	Marco Fidel Suarez	N/A	N/A	N/A	N/A
		PL2	B3	III	Medium
9	Diana Turbay Sector Cultivos - II	N/A	N/A	N/A	N/A
		PL3	B3	II	Low
10	Diana Turbay Sector Cultivos - Torre	VM1	B4	V	High
		N/A	N/A	N/A	N/A
11	El Consuelo	VM1	B3	V	High
		PL3	B3	II	Low
12	El Rosal Rafael Uribe Uribe	N/A	N/A	N/A	N/A
		PL3	B3	II	Low
13	Colinas	VM1	B2	V	High
		PL3	B2	III	Medium
14	Granjas de San Pablo	VM1	B2	V	High
		PL2	B2	IV	High
15	Mirador de Marrocos,	VM1	B2	V	High
		PL3	B2	III	Medium
16	Villas del Recuerdo	VM2	B2	V	High
		PL3	B2	III	Medium
17	Callejón De Santa Barbara Sur Y III	VM2	B2	V	High
		PL3	B2	III	Medium
18	Hospital San Carlos	N/A	N/A	N/A	N/A
		PL3	B4	I	Low
19	Colegio María Cano (El Rosal)- Barrio Zarazota	VM1	B2	V	High
		PL3	B4	I	Low
20	Socorro III - Urbanización Francisco Vega	VM1	B3	V	High
		PL3	B4	I	Low
21	El Portal II	VM1	B3	V	High
		PL3	B2	III	Medium
22	Mirador Sur I y II	VM1	B2	V	High
		N/A	N/A	N/A	N/A
23	Providencia Alta	N/A	N/A	N/A	N/A
		PL3	B3	II	Low
24	Arboleda Sur	VM1	B2	V	High
		PL3	B2	III	Medium
25	Madrid	N/A	N/A	N/A	N/A
		PL3	B2	III	Medium
26	Rio de Janeiro - Pesebre	VM1	B3	V	High
		PL3	B3	II	Low
27	Nueva Esperanza	VM1	B1	V	High
		PL2	B1	V	High

3 | CONCLUSIONS

Between the years 2008 and 2015 occurred 454 events by mass removal phenomena in the Rafel Uribe Uribe locality, with greater intensity in the years 2010, 2011 and 2012, mainly in the months between April and May, and from October to December. During those years, the climate phenomena known as La Niña

was present. This is characterized by an increase in precipitations, which generated an increase in landslide events (Fig. 2). This allows to consider a strong relation between the precipitations as a main trigger for mass removl phenomena in the locality, propitiating affectations such as partial or total collapse in the buildings, compromising the habitability and structural stability at short and medium terms, and hence, the integrity of the people inhabiting them.

From the baseline we encounter that some polygons in the mass removal phenomena hazard map are classified as Low Risk by the District's Office of Planning and the IDEGER. However, in this phase analysis, a large number of mass removal events reportedly have occurred in the last few years, and the number of some families affected and relocated in some polygons (See Table 7). This was evidenced in the following neighborhoods: Los Puentes, Diana Turbay Cultivos, Rincón del Valle, Bosques de San Carlos, La Merced, La Arboleda and Colinas. Then, is necessary to update the susceptibility studies for this locality and to determine the new zones to classify in terms of low, medium or high rish. Additionally, we evidence that the high risk is classified in uninhabited land, which has restriction for urban uses and not in urbanized polygons.

The physical vulnerability index (PVI) in the polygons in the locality of Rafael Uribe Uribe, according to the magnitude of the events registered in the concepts and technical sheets, it is estimated that most of them are within the VM1 to VM3 range, presenting the higher intensity in rain periods for the slopes high zones and PL2 to PL3 for the low parts of the slopes. The predominant type of building in the affected polygons is the masonry, although in some sector one can find houses built out of recycled materials. For this, is estimated that the possible damage index in the buildings is IV and V, Fracture in the structure or partial or total structure collapse; in both cases is required immediate evacuation and the damage percentage could be between 70% and 100%.

Physical vulnerability index by landslide hazard for 31 polygons in the locality of Rafael Uribe Uribe, according to the request type, for lateral pressures is High in 3 polygons, Medium in 12 polygons, Low in 9 polygons and no exposed elements in 7 polygons. For lateral landslides, vulnerability is High in 15 polygons, No polygons for Medium, Low for 4 polygons and 12 polygons with no exposed elements.

Identification and evaluation generates knowledge and information on the derived risk for one or several hazards and allows to settle the basis for the development of other components or politics. Includes the surveillance and observation actions of dangerous phenomena, studies realization, scenario, hazard maps and models, information services on exposition, vulnerability evaluation of the exposed components, qualification and risk visualization, among others, that enable the decision making from the government entities and the implementation of politics for risk management [15].

In this sense, the estimation of physical vulnerability index in the polygons declared as threatened by mass removal phenomena, allows the actors, such as competent public entities and exposed population, to give a specific treatment to each polygon according to the estimated vulnerability index, thus contributing with the actions of preparing and planning the response to possible emergencies, enabling the authorities and population with the accurate implementation of contingency plans and reaction that ensures the best possible management for protecting the integrity and goods of exposed population.

Studies for vulnerability of population exposed to landslides contribute to the planning and occupation of the territory in a safe manner, using information that allows to identify and characterize the risk scenarios that historically have generated risks or disasters within the territory. This enables the local governments to conduct a problem diagnostic as precise as possible and an effective design for the solution.

The locality of Rafael Uribe Uribe is the third most densely populated (254 inhabitants per hectare) in Bogotá; referring to the ZPU where landslides are present, Diana Turbay registers the highest density with 333 persons per hectare, followed by Marco Fidel Suárez which presents 330 persons per hectare and Marruecos with a population density of 253 [5]. Given that the stratification for such sectors corresponds to stratum 1 or 2, exists spatial segregation, which has implications on risk management, meaning that the most segregated population is located in the ZPU in the most susceptible zones, and where the probability of mass removal event occurrence is higher; This added to the poverty situation and the difficulties of access to equipment and infrastructure that eases the anticipation or prevention of emergencies.

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