Evaluation of Seismic Vulnerability of Colonial Typology Houses in Cartagena de Indias, Colombia: Structural Safety Assessment and Public Health Risk Implications

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ABSTRACT

This research evaluated the seismic vulnerability of a group of colonial houses in the historical center of Cartagena using a vulnerability index qualitative method. The study consisted of a review and application of the parameters that make up the method, an analysis of historical-architectural background, a detailed visual inspection and a photographic record, developing a descriptive-type research. The sample consisted in the identification of the 100most representative and predominant colonial houses in the three districts that conform the historical center of Cartagena (Centro, San Diego and Getsemaní),taking 5 for each district; 42 of them were grouped as low houses (LH) and 58 as high houses (HH). The vulnerability index below 15% is established as low, between 15% and 35% as medium, and greater than 35% as high. The results showed the average index for Centro district is 30.54% (medium vulnerability), for San Diego district 40.35% (high vulnerability) and for Getsemaní district 33.42% (medium vulnerability). As conclusion, for the intervention of any colonial house in Cartagena is necessary to make a seismic vulnerability quantitative analysis, supported in a pathological study to qualify the building state, typify the lesions and based in engineering parameters, apply the Colombian Regulation of Earthquake Resistant Construction NSR-10.

Keywords: *colonial house, typology, vulnerability index.*

I. INTRODUCTION

Colombia has architectural wealth of appreciable value inherited from the colonization, that lasted for almost four centuries, by the Spanish, who built in one of their cities, Cartagena de Indias main tourist city if Colombia (10 ° 25′25 "N 75 ° 31′31" O) and Cultural Heritage of humanity declared by UNESCO in 1984, the most complete and extensive system of fortifications in South America. Furthermore, one of the architectural conglomerate of more wealth and relevance materialized in civil, domestic and religious buildings of imponderable aesthetics value[1].The colonial houses in the historical center of Cartagena confer historical value to the city. The constructive form, the materials that were used and the age of these houses are some of the factors that provide them with great architectonic value nowadays [2-4]. The historical center of the city is made up of El Centro, San Diego and Getsemaní districts as shown in Figure 1.

Figure 1. Map of Cartagena historical center[5].

Cartagena in the 50s, and until the end of the 70s, was projected and looked at from modernity, having a development of a contemporary architecture with the Caribbean Sea as tourist destination, without giving the necessary importance to the colonial and military architecture. In the end of the 70s and start of the 80s,aninterest for the patrimony is awakened from the declaration by UNESCO[1].

Today, with the enhancement, conservation of heritage and compliance with international and national legal regulations (Colombian Regulation of Earthquake Resistant Construction NSR-10 [6])it is necessary to evaluate the vulnerability of the set of assets that constitutes our heritage. For the above, it is important to determinate and qualify how vulnerable is the group of houses that constitute the colonial architecture of the city of Cartagena in case of seismic events.

The similarity in architectonic typology, structuration, constitutive materials, pathology and shape of colonial houses facilitates the evaluation of a representative sample and in this waydetermine the general performance for the rest of the houses.

Due to the importance of the Cartagena domestic architecture, in recent years architects and engineers have been interested in knowing the details of constructive techniques, materials and parameters used for construction. Today, it is known that in the construction of colonial houses factors of war nature or ancestral influences of social and economic kind prevailed rather than any minimum intention to protect the city from any telluric event or other natural accident, which were little known for that time.

The formal configuration of these domestic buildings, due to its merely empiric construction, presents certain instability caused mainly by the lack of unity in its constructive conformation, which is given as a sequence of space exposed to forces in all directions. Thus, the building is a mass vulnerable to any movement of the ground, and if it is added the fact of not contemplate, by lack of knowledge, basic principles in the construction of a building, such as scale, height, proportion and symmetric; it is obtained as result a set of building extremely sensitive to naturals phenomena, whether telluric or any other kind.

For the reasons above, this research seeks to know what the dominant vulnerability index is in the colonial typology houses due its inherent structuring of the architectural configuration itself.

II. METHOD

This research was based on the application of the vulnerability index method by Benedetti and Petrini, which indicates the most important parameters that control the damage that an earthquake can cause in any building, qualifying diverse aspects and trying to distinguish the differences in the same type of building or typology.

The method evaluates 11 parameters, which qualified in their maximum value gives as result 382.55. Below it is a table with these parameters [7].

Table 1. Numerical scale of Benedetti's vulnerability index[8].

	Parameter	KiA	KiB	KiC	KiD	Wi
1	Organization of resistant system	0	5	20	45	1.00
2	Quality of the resistant system	0	5	20	45	0.25
3	Conventional resistance	0	5	20	45	1.50
4	Building position and foundation	0	5	20	45	0.75
5	Horizontal diaphragms	0	5	20	45	1.00
6	Plant configuration	0	5	20	45	0.50
7	Elevation configuration	0	5	20	45	1.00
8	Maximum separation between walls	0	5	20	45	0.25
9	Roof type	0	5	20	45	1.00

10	Non-structural elements	0	5	20	45	0.25
11	Conservation state	0	5	20	45	1.00

The method works with a rating system between 0 and 45. Rating quality conditions A, B, C and D, where A is optimal and D is not favorable; and weight (Wi) factors that corresponds to the weight of each assigned parameters. The Ki and Wi factors are the result of the obtained data in each seismic event in a region. The vulnerability index is calculated from the sum of the multiplication between the parameter qualification (Ki)and its weight (Wi), as shown in (1) equation [7].

$$VI = \sum (K_i W_i) \ (1)$$

To know the vulnerability index in a normalized scale, the vulnerability index value obtained is divided by the possible vulnerability index value, and then it is multiplied for 100 to calculate the percent, as shown in (2) equation.

$$\%VI = \frac{VI}{382.55} \times 100\ \% \qquad (2)$$

In this project, the vulnerability index (VI) was determined for the high colonial houses (HH) predominant in the Centro district and low colonial houses (LH) in San Diego and Getsemaní districts.

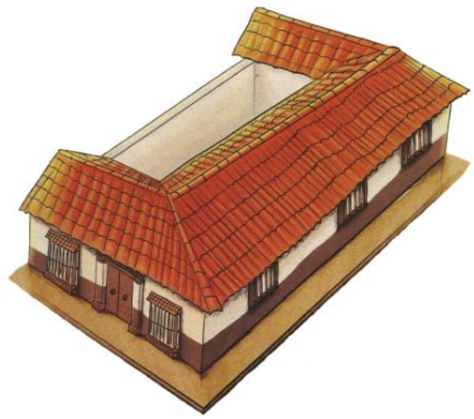

Figure 2. Isometric view of the low colonial house [2].

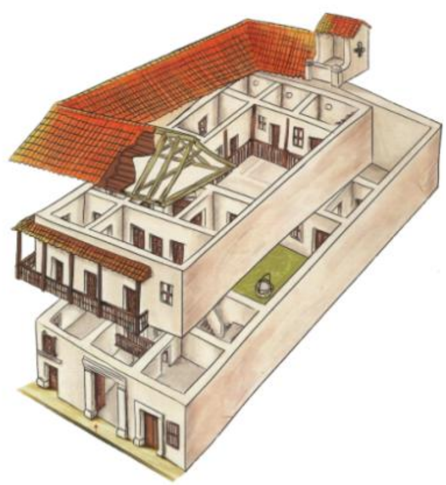

Figure 3. Isometric view of the high colonial house[2].

2.1. Data collection techniques

Figure 4 shows the activities followed in this research for the collection of data needed.

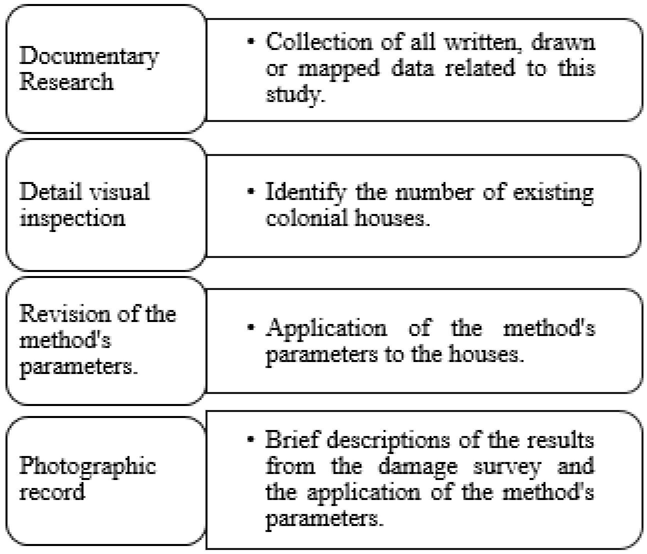

Figure 4. Data collection procedure

2.2. Data analysis techniques.

Each parameter was classified and qualified following Benedetti and Petrini method for each of the houses studied in the three districts that make up the historical center of Cartagena de Indias. The objective was to achieve a proper characterization of vulnerability index that would allow the identification of the most vulnerable district. Finally, all the collected data was transcribed, analyzed, and registered in a report.

III. RESULT & DISCUSSION

The vulnerability index with a value less than 15% is established as low, between 15% and 35% as medium, and greater than 35% as high. The results of this research showed that the average index for Centro district is 30.54%, for San Diego district 40.35% and for Getsemaní district 33.42%. Therefore, the San Diego district has a high vulnerability index, and Centro and Getsemaní districts have a medium vulnerability index.

3.1. Vulnerability index of colonial houses in Centro district

Table 2. Average vulnerability index of colonial houses in Centro district[9].

PARAMETERS	HOUSE N°1		HOUSE N°2		HOUSE N°3		HOUSE N°4		HOUSE N°5	
	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi
P1	C	20.00	C	20.00	C	20.00	C	20.00	C	20.00
P2	D	11.25	D	11.25	D	11.25	D	11.25	D	11.25
P3	A	0.00	A	0.00	A	0.00	A	0.00	A	0.00
P4	A	0.00	A	0.00	A	0.00	A	0.00	A	0.00
P5	C	15.00	C	15.00	C	15.00	C	15.00	C	15.00
P6	D	22.50	D	22.50	D	22.50	C	12.50	D	22.50
P7	A	0.00	A	0.00	C	25.00	A	0.00	C	25.00
P8	A	0.00	A	0.00	A	0.00	A	0.00	A	0.00
P9	B	15.00	C	25.00	C	25.00	C	25.00	B	15.00
P10	A	0.00	A	0.00	A	0.00	A	0.00	A	0.00
P11	C	25.00	C	25.00	D	45.00	A	0.00	A	0.00
Vulnerability Index (VI)	VI	**108.75**	VI	**118.75**	VI	**163.75**	VI	**83.75**	VI	**108.75**
		28.45%		**31.07%**		**42.84%**		**21.91%**		**28.45%**
	Medium VI		Medium VI		High VI		Medium VI		Medium VI	

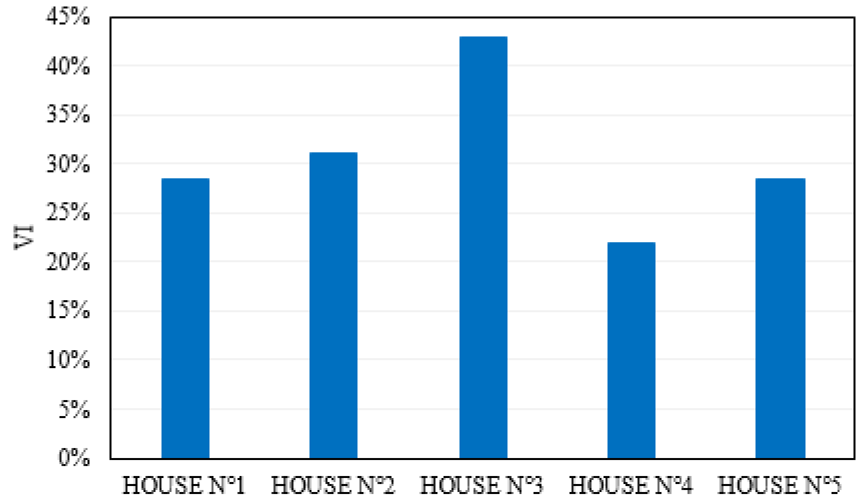

Figure 5. Vulnerability index of colonial houses in Centro district [9].

From the results obtained for Centro district through the evaluation of vulnerability index, the tendency of the index for this district ismedium-high. For a recurrence of an A type class, in the 3, 4, 7, 8, 10 and 11 parameters, a value of 21.91% is presented. Moreover, for a recurrence of a D type class, which corresponds to the highest value in the classification of the method for 2, 6 and 11 parameters, a peak value of 42.84% is presented.

3.2. Vulnerability index of colonial houses in San Diego district.

Table 3. Average vulnerability index of colonial houses in San Diego district [10].

PARAMETERS	HOUSE N°1		HOUSE N°2		HOUSE N°3		HOUSE N°4		HOUSE N°5	
	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi
P1	C	20.0	C	20.00	C	20.00	C	20.00	C	20.00
P2	D	11.3	D	11.25	D	11.25	D	11.25	D	11.25
P3	A	0.0	A	0.00	A	0.00	A	0.00	A	0.00
P4	A	0.0	A	0.00	A	0.00	A	0.00	A	0.00
P5	D	45.0	A	0.00	D	45.00	D	45.00	D	45.00
P6	C	12.5	A	0.00	C	12.50	D	22.50	B	2.50
P7	A	0.0	A	0.00	A	0.00	A	0.00	A	0.00
P8	C	6.3	C	6.25	C	6.25	A	0.00	A	0.00
P9	D	45.0	D	45.00	D	45.00	D	45.00	D	45.00
P10	B	0.0	C	6.25	B	0.00	B	0.00	B	0.00
P11	D	45.0	D	45.00	A	0.00	D	45.00	A	0.00
Vulnerability Index (VI)	**VI**	**185.00**	**VI**	**133.75**	**VI**	**140.00**	**VI**	**188.75**	**VI**	**123.75**
		48.40%		**34.99%**		**36.63%**		**49.38%**		**32.37%**
	High VI		**Medium VI**		**High VI**		**High VI**		**Medium VI**	

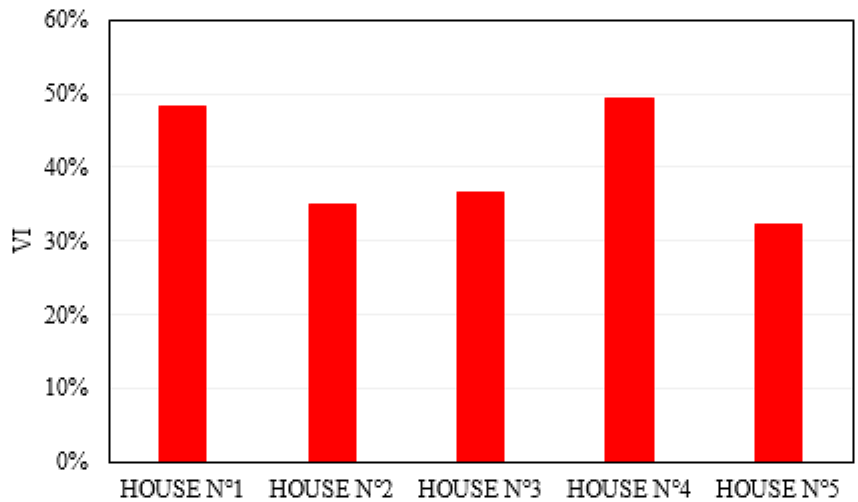

Figure 6. Vulnerability index of colonial houses in San Diego district[10].

From the results obtained for San Diego district through the evaluation of vulnerability index, the tendency of the index for this district is high. For a recurrence of a D type class, in the 2, 5 and 9 parameters, a value of 32.37% is presented. Moreover, for a recurrence of a D type class, which corresponds to the highest value in the classification of the method for 2, 5, 6, 9 and 11 parameters, a peak value of 49.38% is presented.

3.3. Vulnerability index of colonial houses in Getsemaní district.

Table 4. Average vulnerability index of colonial houses in Getsemaní district [11].

PARAMETERS	HOUSE N°1		HOUSE N°2		HOUSE N°3		HOUSE N°4		HOUSE N°5	
	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi	CLASS	Ki*Wi
P1	C	20.0	C	20.00	C	20.00	C	20.00	C	20.00
P2	C	6.25	D	11.25	C	6.25	C	6.25	D	11.25
P3	A	0.0	A	0.00	A	0.00	A	0.00	A	0.00
P4	A	0.0	A	0.00	A	0.00	A	0.00	A	0.00
P5	D	45.0	D	45.00	D	45.00	D	45.00	D	45.00
P6	A	0.0	D	22.50	D	22.50	A	0.00	A	0.00
P7	A	0.0	A	0.00	A	0.00	A	0.00	A	0.00
P8	A	0.0	B	1.25	A	0.00	A	0.00	A	0.00
P9	B	15.0	C	25.00	B	15.00	B	15.00	D	45.00
P10	B	0.0	B	0.00	D	11.25	B	0.00	B	0.00
P11	B	5.0	A	0.00	D	45.00	B	5.00	D	45.00
Vulnerability Index (VI)	**VI**	**91.25**	**VI**	**125.00**	**VI**	**165.00**	**VI**	**91.25**	**VI**	**166.25**
		23.87%		**32.70%**		**43.17%**		**23.87%**		**43.49%**
	Medium VI		**Medium VI**		**High VI**		**Medium VI**		**High VI**	

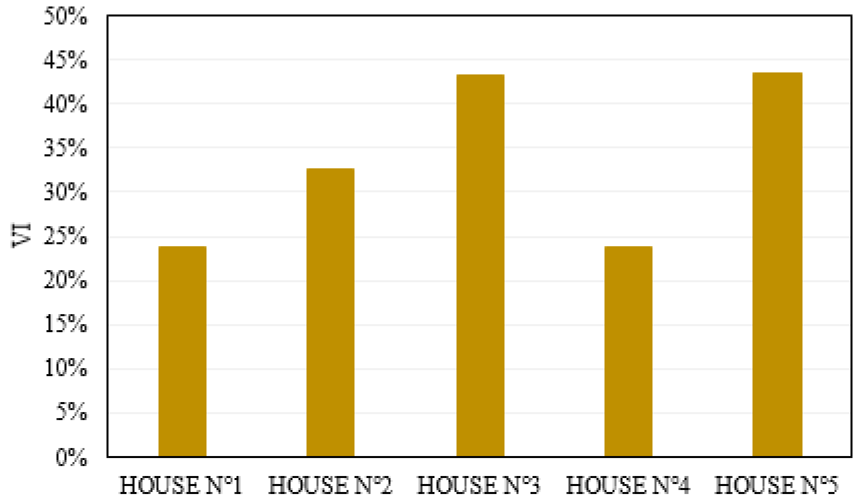

Figure 7. Vulnerability index of colonial houses in Getsemaní district [11].

From the results obtained for Getsemaní district through the evaluation of vulnerability index, the tendency of the index for this district is medium-high. For a recurrence of an A type class, in the 3, 4, 6 and 7 parameters, a value of 23.87% is presented. Moreover, for a recurrence of a D type class, which corresponds to the highest value in the classification of the method for 2, 5, 9 and 11 parameters, a peak value of 43.49% is presented.

3.4. Average vulnerability index of colonial houses in Centro, San Diego and Getsemaní districts.

Table5. Average vulnerability index of colonial houses in the three district of historical center in Cartagena.

District	Average vulnerability index
Centro	31%
San Diego	40%
Getsemaní	33%

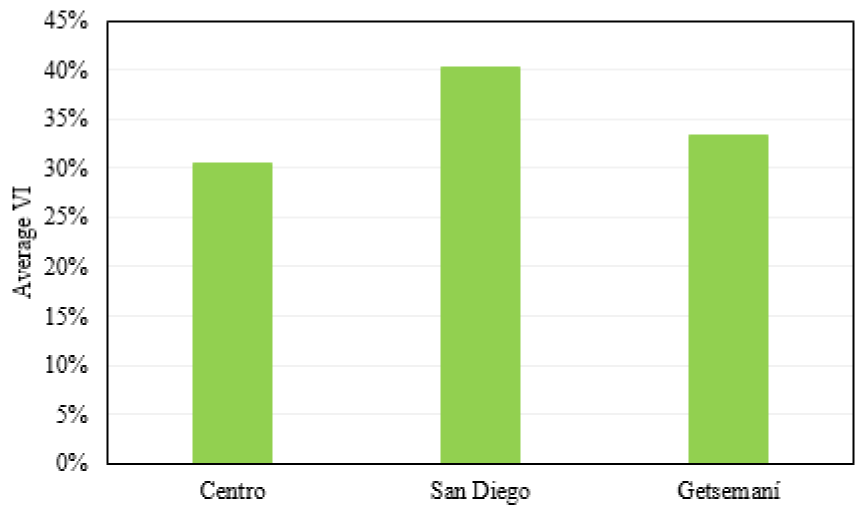

Figure 8. Average vulnerability index of colonial houses in the three district of historical center in Cartagena.

IV. CONCLUSION

This research approached an evaluation of the seismic vulnerability of colonial typology houses in Cartagena de Indiasusing a vulnerability index qualitative method giving as result that the houses in the historical center of this city have a medium-high vulnerability index. Therefore, it is recommended, for the evaluation and intervention of any colonial type house in any of the three district that made up the historical center of Cartagena de Indias, to carry out a seismic vulnerability quantitative analysis using for this purpose the provisions of Chapter A.10 of Colombian Regulation of Earthquake Resistant Construction NSR-10 [6].

Furthermore, this research characterized and detected structuration aspects and recurrent pathology in the colonial type houses. As conclusion, the following three aspects present in the colonial housescan lead to a poor performance of them in case of an earthquake:

1. The poor quality of the walls in both materials and construction procedures, regular state of the buildings at wall level, regular state ofthe wood mezzanines and roofs, the little integrity or union between orthogonal walls.
2. The high housesdo not present a rigorous diaphragm at mezzanine level, with the extenuating that strong beams that make up the mezzanine are connected to the wall through holes that create a fail plane or discontinuity between walls from first and second floor.
3. The roofs of colonial houses arepairs and rows type, or pair and knuckle type, both tightened. These roofs are gable type with an inclination between 35 and 45 degrees, what leads to important forces in its horizontal component, which contributes to collapse of the walls when the beams stop working.

REFERENCES

1. *W. Rivera, "La ingeniería estructural, la normativa de construcción colombiana vigente y la conservación del patrimonio arquitectónico de las edificaciones del período colonial en Cartagena de Indias", 2019.*
2. *"Cartagena Pregón de la Libertad – Bicentenario Cartagena de Indias 1811-2011", Volume 1, Publicaciones Semana, Colombia, 2011, pp. 47-49.*
3. *"Arquitectura cartagenera: 5 siglos de historia", El Universal, December 2011,availablefrom http://www.eluniversal.com.co/suplementos/dominical/arquitectura-cartagenera-5-siglos-de-historia-57900*
4. *G. Téllez and E. Moure, "Arquitectura doméstica Cartagena de Indias", Corporación Nacional de Turismo, Colombia, 1982.*
5. *"Plazas y Calles de Cartagena de Indias". [Internet] [cited January 2018], available from http://www.cartagenacaribe.com/arquitectura/plazasycalles/mplocalizacion.htm*
6. *NSR-10, "Reglamento Colombiano de Construcción Sismo Resistente", Ministerio de Ambiente, Vivienda y Desarrollo Territorial, Colombia, 2010.*
7. *E. Acero, "Aproximación al comportamiento estructural de edificaciones en tierra de la arquitectura colonial", 2012, availablefromhttp://bdigital.unal.edu.co/11493/1/elizabethaceromatallana.2012.pdf*
8. *A. Caballero, "Determinación de la vulnerabilidad sísmica por medio del método de índice de vulnerabilidad en las estructuras ubicadas en el centro histórico de la ciudad de Sincelejo, utilizando tecnología de sistema de información geográfica", Sincelejo, Colombia, 2007.*
9. *M. Ospino and M. Torres, "Vulnerabilidad de casas altas de tipo colonial ubicadas en el centro histórico de la ciudad de Cartagena", Universidad de Cartagena, Cartagena de Indias, Colombia, 2016.*
10. *O. Barrera and O. Nieves, "Determinación de la vulnerabilidad en las casas coloniales ubicadas en el barrio de San Diego de la ciudad de Cartagena", Universidad de Cartagena, Cartagena de Indias, Colombia, 2015.*
11. *C. Fortich and L. López, "Determinación de la vulnerabilidad en las estructuras ubicadas en casas coloniales en el barrio Getsemaní de la ciudad de Cartagena", Universidad de Cartagena, Cartagena de Indias, Colombia, 2016.*