Nonlinear dynamic analysis of steel buildings subjected to earthquakes

Análisis dinámico no lineal de edificios de acero sometidos a sismos

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Abstract

Non-linear dynamic analyses methods generally provide a more adjusted modeling of the structural response for strong seismic events. Such a dynamic seismic non-linear evaluation took place for six buildings: two 5 story-height, two 12 story-height and two 20 story-high and with a regular configuration. The structural systems of the buildings complied to the NSR-10 (Colombian earthquake resistant standard) and with the seismic microzoning of Bogotá.

The analysis done to the previous structures used non-linear methodologies along with two time- histories corresponding to two well recorded earthquakes: Quetame earthquake circa 2008 and the Mesa de los Santos earthquake circa 2015. Said events characterized by records at Bogotá D.C. by the RAB (network of accelerometers of Bogotá). A structural evaluation using the nonlinear approach of a finite element software and following the FEMA 356 guidelines, the structural response to 81 seismic signals from the Mesa de los Santos earthquake and 78 from the Quetame earthquake helped in understanding the simulated behavior. Said signals included three perpendicular ground movements corresponding to the north-south, east-west and vertical directions. With the results of the non-linear dynamic analysis, plastic hinges helped in understanding the nonlinear structural response when the earthquakes hit separately. Based on the results, sway maps showing the results in the Y and X directions, clustered the most affected areas of the city. At the same time, a thorough analysis of moment connections at the first floor, at an intermediate floor and at the last floor of the buildings showed the capacity of the original design.

The results suggest that steel buildings have a better structural performance when compared with reinforced concrete buildings that were also analyzed (nonlinear analysis) with real earthquake (in soft soils) in previous investigations.

Keywords: *Nonlinear dynamic analysis, seismic behavior, steel buildings, seismic soil response, resistant steel moment frames*

Resumen

Los métodos de análisis dinámico no lineal generalmente proporcionan modelos más ajustados de la respuesta estructural para fuertes movimientos sísmicos. Por ello, se realizó una evaluación sísmica no lineal dinámica de seis edificaciones: dos de 5, dos de 12 y dos de 20 pisos de altura y con una planta regular. El sistema estructural de los edificios fue diseñado de acuerdo a la NSR-10 (norma sismo resistente colombiana) y con la microzonificación sísmica de Bogotá.

Los seis edificios fueron analizados utilizando metodologías no lineales y sometidos a los movimientos sísmicos de dos terremotos: el terremoto de Quetame de 2008 y el terremoto de Mesa de los Santos de 2015, ambos registrados en Bogotá DC por el RAB (red de acelerómetros de Bogotá). Utilizando el módulo no lineal de un software de elementos finitos y siguiendo las pautas de FEMA 356, se evaluó la respuesta de los edificios a 81 señales sísmicas del terremoto de Mesa de los Santos y 78 del terremoto de Quetame. Las señales incluían tres movimientos de tierra perpendiculares correspondientes a las direcciones norte-sur, este-oeste y vertical. Con los resultados del análisis dinámico no lineal, se evaluaron las rótulas plásticas no lineales de los elementos estructurales de las edificaciones para los dos sismos analizados. Con base en los resultados, se construyeron mapas para mostrar las derivas (distorsiones de entrepiso) en la dirección Y, las derivas en la dirección X y las derivas totales. Asimismo, se verificaron las conexiones en el primer piso, un piso intermedio y el último piso de los edificios analizados.

Los resultados sugieren que los edificios de acero tienen un mejor desempeño estructural en comparación con los edificios de concreto reforzado que también fueron analizados (análisis no lineal) con terremotos reales (en suelos blandos de Bogotá) en investigaciones anteriores.

Palabras clave: Análisis dinámico no lineal, comportamiento sísmico, edificaciones en acero, respuesta sísmica del suelo, pórticos resistentes a momento en acero

1. Introduction

The seismic behavior of structures depends on the type of soil on which they are settled, its geometry, mechanical and dynamic properties, and soil-structure interaction. Wave propagation in the soil induces vibrations that are received by the foundation and then by the structure.

In any city, the microzonation helps in reducing seismic risk and has proved to be an acceptable methodology. Its objective is to evaluate seismic hazard levels and local effects, to establish areas with similar seismic behavior and specify in each of them the seismic-resistant design requirements that must be considered to generate consistent reliability in building design (Bernal, 2015).

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In 1997, the first seismic microzonation study was implemented in Bogota, identifying four different soil areas with different acceleration spectra (Ingeominas and UNIANDES, 1997). Then, in 2010, the updated seismic microzonation of the city took place. In there, Bogota got 16 seismic response areas, each with different degrees of seismic hazard (FOPAE, 2010).

Since 1999, it was possible to record many seismic signals when the Accelerometer Network of Bogota (RAB) was put into operation. With this information, it is possible to analyze the surface variation of seismic parameters and the spectral response of soils where the stations are currently working.

Over the last 15 years, detailed studies of Bogota's geotechnical past helped in setting the dynamic behavior and the effect of the local seismic response by the geotechnical strata on constructed buildings. A detailed example of this type of study is shown in (Carrasco and Cardozo, 2015). Also, since the beginning of the RAB, and according to the database collected by the Bogota's Fund for the Prevention and Attention of Emergencies (FOPAE, 2010) (SIRE, 2008), more than 200 different local hazard studies complemented the implementation of the original microzonation from the late 2000s (Alcaldía de Bogotá, 2001), considering different seismic hazard scenarios in each specific area. At the same time, by means of the local act 523 of 2010 (Bogota Mayor's Office, 2010), the current seismic microzonation became effective, dividing the city into 16 areas as estimated from the FOPAE study (FOPAE, 2010).

Considering the record of the Quetame earthquake in 2008 (Ingeominas, 2008) and the Mesa de los Santos earthquake in 2015 (SGC, 2015), the present study focuses in determining the seismic response of 6 steel moment resisting / braced buildings with 5,12 and 20 stories. For each building, the earthquake acted in the three mutually perpendicular directions, x, y and z, to identify the areas of Bogota with the greatest sway demands and consequently the damage level. This will be done by means of a nonlinear dynamic analysis.

Previous research used signals filtered by soft soil as in(Zárate et al., 2005). (Ruiz et al., 2008) used nonlinear dynamic analyses on 2D frames of several buildings of different heights located in Bogota and subjected to seismic signals in rock. These examples provided the first trends on the most demanding areas of the city for buildings, based on their height and soil conditions (site effects). Next, (Ruiz et al., 2008) took filtered signals from soft soils in Bogota and areas near the hills, showing that tall buildings will have a higher damage level in soft soil strata than compared to those in rocky strata. (Later et al., 2009) used the same 2D frames and forced them by the signals obtained by the RAB specifically the 2008 Quetame earthquake (Ingeominas, 2008). This last work provided a deeper understanding of the subject since it was possible to use signals from a real earthquake to analyze buildings throughout the city. However, one of the recommendations of said study was the need to perform three-dimensional nonlinear analyses. For this reason, (Ruiz et al., 2012) conducted a three-dimensional nonlinear analysis of real buildings subjected to the records of a real event recorded by various accelerometers in Bogota. This was an unprecedented effort since it corresponds to the evaluation of structures subjected to three-dimensional nonlinear analysis of a real earthquake that was not scaled or modified in any way. (Bernal et al., 2015) conducted a similar study for another earthquake that occurred at a greater distance than the Quetame earthquake and was also recorded by the RAB: The Mesa de los Santos earthquake. However, to present date, all research done used exclusively reinforced concrete buildings. For this reason, the present study is an innovation, as it includes structural steel buildings and nonlinear dynamic modeling. Similarly, but in steel structures, using historical records of great significance, it was possible to determine that steel frames subjected to seismic signals of historical importance (Northridge, Loma Prieta, Imperial Valley) center the desired failure mechanisms (object of a good steel seismic-resistant design happening in beams, especially away of the protected area (beam-column joint), and less probably in columns (Sultana and Youssef, 2016). However, this desired failure mechanism is only a theoretical concept, because inelastic sway increases rapidly due to lateral instability.

2. Materials and methods

2.1. Materials and design loads

(Table 1) shows the mechanical parameters of the steel used (ASTM A572 GR50), (Table 2) shows the magnitudes of dead loads and (Table 3) shows the magnitudes of live loads used for modeling the various structures:

Table 1. *Mechanical parameters of materials used for beams and columns*

Parameter	Unit	ASTM A572 GR50
Yield stress (Fy)	MPa	345
Ultimate stress (Fu)	MPa	400
Modulus of elasticity (E)	MPa	200,000

Table 2. *Dead loads used in the present building design*

Parameter	Unit	Dead Load
Plate Weight	kN/m^2	3.53
Steel Deck	kN/m^2	0.09
Dividing walls	kN/m^2	2.94

Table 3. *Live loads used in the present building design*

Parameter	Unit	Live Load
Residential use	kN/m^2	1.8

The magnitudes of the imposed loads correspond to those set in the applicable Colombian regulations for residential buildings (AIS, 2010). It is important to mention that the NSR-10 standard (AIS, 2010), regarding seismic design, is an adapted version to the local context of the original document ATC-63 (Applied Technology Council), (ATC, 2009), with specific aspects of the NEHRP (National Earthquake Hazard Reduction Program), (FEMA, 1998) and (FEMA, 2000).

2.2 Seismic signals

Two earthquakes of interest, the Quetame earthquake recorded in 2008 (Ingeominas, 2008) and the Mesa de los Santos earthquake recorded in 2015 (SGC, 2015) were the main seismic force used in the present research. These two records had a magnitude greater than 5.0 on the local Richter scale along the Colombian territory (Bernal, 2015).

2.3 Building Code

Steel buildings complied to the NSR-10 (AIS, 2010), having as seismic load, the spectra of the 2010 seismic microzonation, Lacustrine – 500 and Foothill – B, for the city of Bogota. Six buildings were designed, two of 5, two of 12 and two of 20 stories high. For structural elements W shapes covered the needs of both beams and columns. A "Steel deck" or collaborating slab was the best solution for the flooring system.

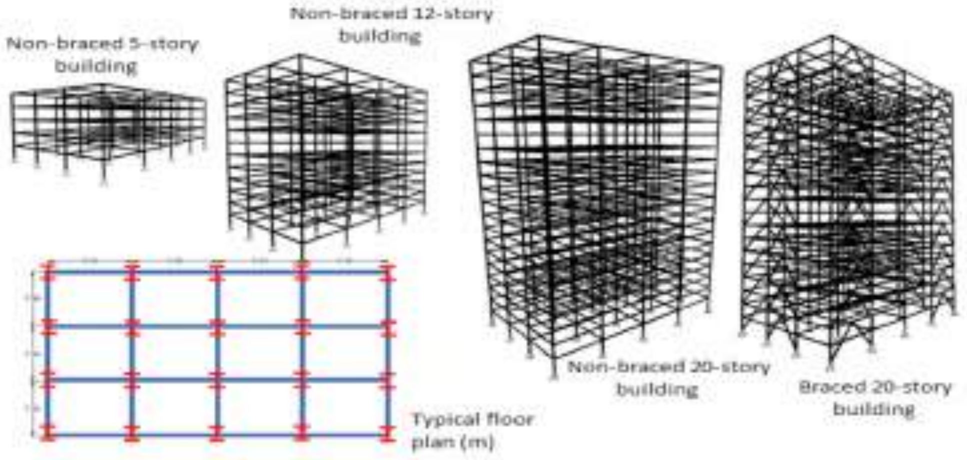

Figure 1. *Structural diagrams and typical floor plan of the structures under study (adapted from García, 1996)*

(Figure 1) shows the typical floor plan used for the design of the six buildings. Said buildings had in the X direction, four (4) bays, 9.0 m each and in the Y direction, three (3) bays, 7.5 meters each. The slab followed the direction of the load-bearing frames (placed in the X direction). The design parameters were global sway and mechanical capacity demand from the various load combinations.

2.4 Design spectra

The two design spectra selected, were the highest and lowest acceleration spectra available in the seismic microzonation of Bogota City. These spectra correspond to FOOTHILL – B with a spectral acceleration of 0.713 g and LACUSTRINE – 500, with a spectral acceleration of 0.356 g see (Figure 2).

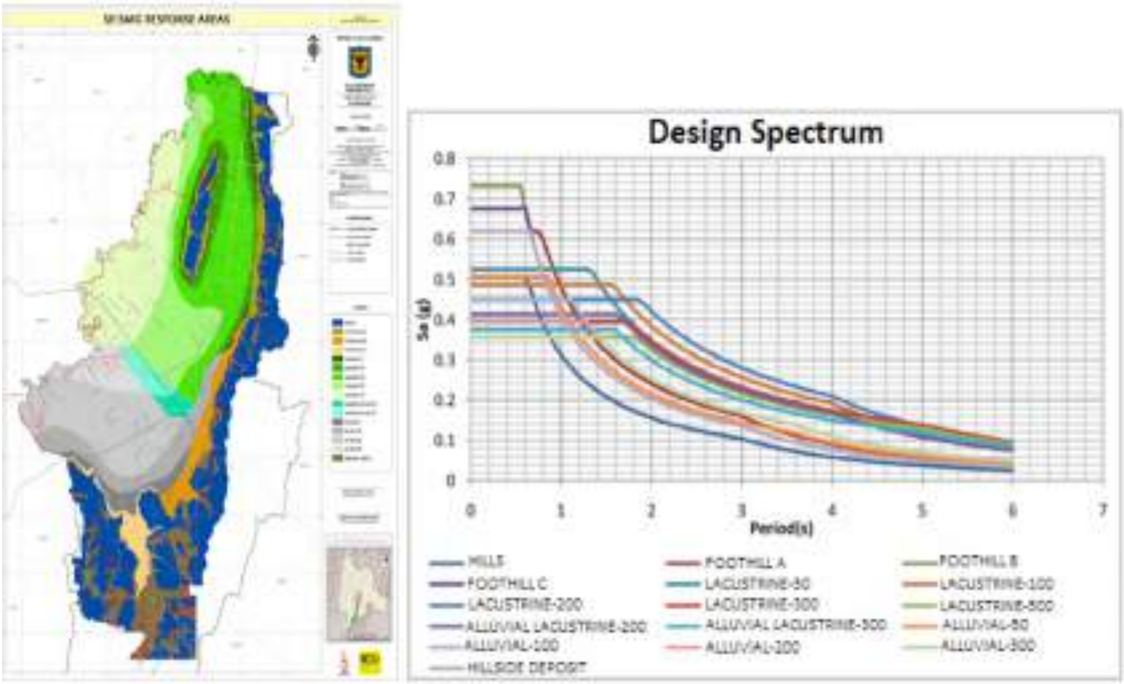

Figure 2. Design Spectra of the Seismic Microzonation of Bogota. Adapted from (Ruiz et al., 2012)

2.5 Structural Element Design

Buildings complied design following the Colombian Regulations for Seismic Resistant Construction, NSR-10 (AIS, 2010). The design effort also complied with ANSI/AISC 360 (AISC, 2016), ANSI/AISC 358 (AISC, 2016a), ANSI/AISC 341 (AISC, 2016b) and (Brockenbrough, 1998). The 5-story buildings did not require bracing on the structure to control the maximum sway demand. However, the 12-story and 20-story buildings required braces in the façade in each of the X and Y directions to control lateral displacements due to lateral action.

Table 4. Profiles used in structural elements of the buildings under analysis

Element	***Profile***	***Building designed according to Lacustrine – 500 spectrum***			***Building designed according to Foothill – B spectrum***			***Axis***
		5 stories	*12 stories*	*20 stories*	*5 stories*	*12 stories*	*20 stories*	
Joists	*W 10 x 33*	*X*			*X*			
	W 10 x 12		*X*	*X*		*X*	*X*	
Beams	*W 12 x 53*	*X*			*X*			
	W 12 x 14		*X*	*X*		*X*	*X*	
Columns	*W 36 x 135*	*X*						*A1, B1, C1, D1, B4, C4, A5, D5.*
	W 36 x 231	*X*						*B2, C2, A3, D3, B5, C5.*
	W 30 x 90	*X*						*A2, D2, A4, D4.*
	W 36 x 256	*X*						*B3, C3.*
	W 36 x 232				*X*			*A1, B1, C1, D1, B4, C4, A5, D5.*
	W 36 x 305				*X*			*B2, C2, A3, D3, B5, C5.*
	W 30 x 136				*X*			*A2, D2, A4, D4.*
	W 36 x 361				*X*			*B3, C3.*
	W 14 x 283					*X*		*B2, B3, B4, C2, C3, C4.*
	W 14 x 311					*X*		*A3, D3.*
	W 14 x 398					*X*		*A2, A4, D2, D4.*
	W 14 x 426					*X*		*B1, C1, B5, C5.*
	W 14 x 500					*X*		*A1, D1, A5, D5.*
	W 14 x 211		*X*					*B1, C1, B5, C5.*
	W 14 x 311		*X*					*A3, D3.*
	W 14 x 398		*X*					*A2, A4, D2, D4.*
	W 14 x 426		*X*					*B2, B3, B4, C2, C3, C4.*
	W 14 x 500		*X*					*A1, D1, A5, D5.*
	W 14 x 398				*X*			*B2, B3, B4, C2, C3, C4.*
	W 14 x 550				*X*			*A3, D3.*
	W 14 x 605				*X*			*B1, B5, C1, C5.*
	W 14 x 730				*X*			*A1, A2, A4, A5, D1, D2, D4, D5.*
	W 36 x 411						*X*	*B1, B2, B3, B4, B5, C1, C2, C3, C4, C5.*
	W 14 x 426						*X*	*A3, D3.*
	W 14 x 605						*X*	*A2, A4, D2, D4.*
	W 14 x 730						*X*	*A1, A5, D1, D5.*
X Bracing	*W 10 x 33*		*X*			*X*		
	W 10 x 88						*X*	
	W 12 x 96			*X*				
Y Bracing	*W 10 x 56*					*X*		
	W 12 x 96			*X*				
	W 10 x 49		*X*					

(Table 4) summarizes the structural shapes used in each of the buildings under analysis and according to the selected orientation, following the geometrical distribution shown in (Figure 1).

2.6 Connection design

It was possible to design three connections for each set of buildings, for a total of 18 connections designed as follows: one connection on the highest floor, one on the middle height floor and one on the ground floor. For this purpose, the guidelines established in the following documents NSR-10 (AIS, 2010), ANSI/AISC 360 (AISC, 2016), ANSI/AISC 358 (AISC, 2016a) and ANSI/AISC 341 (AISC, 2016b) helped in the designing process. It is important to mention that all studied connections belong to axis 1. This, to ensure that the weak point was not the connections but rather the beam elements, i.e., to ensure that the beams, columns and braces behave as the possible weak points instead of promoting failures at the connections.

For the 5-story buildings, the control points remained at floors 1, 3 and 5; for the 12-story building, the control points in floors 1, 6 and 12. Similarly, for the 20-story building, the control points were placed on floors 1, 10 and 20.

Tearing capacity check used the internal forces coming from the several load combinations. In all, the 18 connections passed this capacity check. End plate moment connections were the typical geometry selected for all types of moment connections These connections are prequalified for the seismic resistance system (4E and 4ES type) following the provisions of AISC 360/358 and 341. (Table 5) shows a summary of the typical connection for 5, 12 and 20-story buildings:

Table 5. *Typical connection details*

Element	***Geometry***	***Element***
Bolt diameter	*1 1/2 in.*	*Bolt diameter*
Bolt grade	*A325*	*Bolt grade*
End-plate thickness	*1 1/4 in (32 mm)*	*End-plate thickness*

To evaluate the tearing capacity between the end-plate and column flange, a computation of stress concentration at the standard hole limit state was enough. This, according to AISC 360/358 J.3.10, resulting in higher demands as the height of the building became lower.

Table 6. *Typical end-plate moment connection tearing demands*

Building	***Design spectrum***	***Tearing shear (kN)***
20 stories	*LACUSTRINE-500*	*12218*
20 stories	*FOOTHILL-B*	*12218*
12 stories	*LACUSTRINE-500*	*3586*
12 stories	*FOOTHILL-B*	*3586*
5 stories	*LACUSTRINE-500*	*1969*
5 stories	*FOOTHILL-B*	*3909*

(Table 6) shows the reported values of tearing forces expected in the evaluated connections, as a function of height and seismic demand.

2.7 Structural weight

The total structural weight was a function of unit weight considering the number of the structural elements (columns, beams, joists, braces) and it was an automatic report from the ETABS® finite element software. (Table 7) shows the summary of the various structural weights (after design) showing the minor changes as a function of seismic demand.

Table 7. *Total structural weight as a function of structural design and seismic demand*

Building Story height	**Units**	**Weight**	**Spectrum**	**kN/m^2**
5	kN	2999.5	Lacustrine	7.41
5	kN	29616.4	Foothill	7.31
12	kN	69784.1	Lacustrine	7.18
12	kN	69677.1	Foothill	7.17
20	kN	122667.1	Lacustrine	7.57
20	kN	122101.4	Foothill	7.54

2.8 Seismic signals used

By means of the RAB stations, it was possible to obtain the acceleration records for the Quetame earthquake in 2008 (Ingeominas, 2008) and the Mesa de los Santos earthquake in 2015 (SGC, 2015). Currently, the RAB has 30 stations distributed throughout the city to have a comprehensive record of seismic activities, as shown in)Figure 3).

As an example of the records used, (Figure 3) shows the record for the Quetame and Mesa de los Santos earthquakes, according to the Jardín Botánico station.

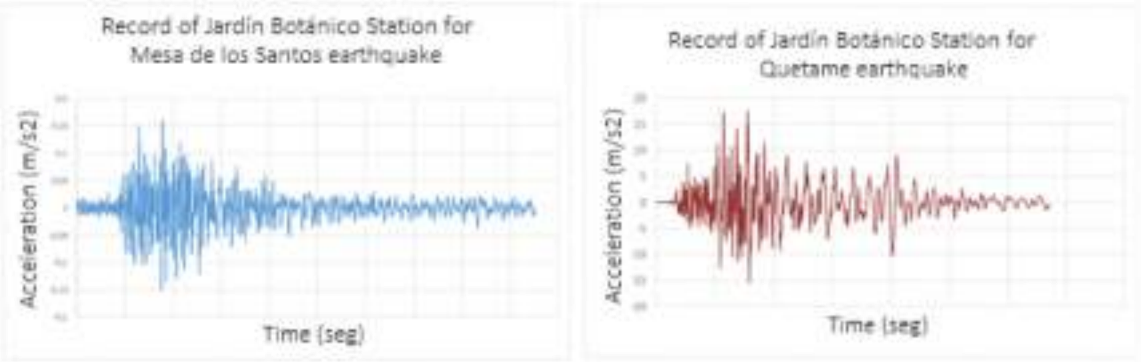

Figure 3. *Botanical Garden Station record*

During the Quetame earthquake in 2008, the RAB recorded the acceleration history at a total of 26 stations. For the Mesa de los Santos earthquake in 2015, a total of 28 stations recorded the event used for the present analysis see (Figure 4).

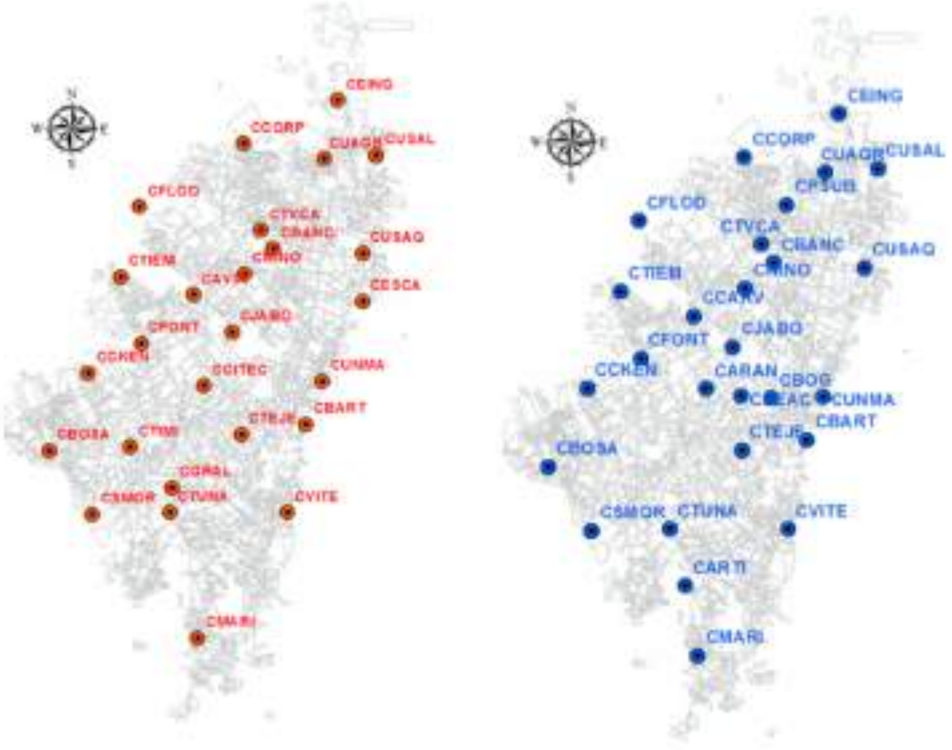

Figure 4. *RAB stations with available records of the Quetame (left) and Los Santos (right) earthquakes in the city of Bogota*

2.9 Nonlinear modeling

ETABS® finite element software helped in performing the nonlinear analysis in steel buildings, following FEMA 356 guidelines (FEMA, 2000), setting the cases of analysis according to the signals recorded for each one of the seismic events. At the same time, reporting the theoretical formation of plastic hinges in beams, columns and bracing elements, according to ASCE 41 - 13. This, to simulate the level of plastic damage in each case. Even though there are methodologies that suggest that it is possible to not require this type of complexity in the evaluation of the seismic behavior of a structure subjected to a seismic signal (Montuori et al., 2020), this is necessary for the present study, given the complexity of Bogota soils. These soils have been studied locally, and there are design spectra for each sector of the city.

The 81 seismic signals for the Mesa de los Santos earthquake and the 78 signals for the Quetame earthquake are part of said nonlinear analysis. Each station reports three signals corresponding to the north-south, east-west and vertical directions, thus, matching the "Time History" function available for ETABS®. The same procedure was performed with each of the signals recorded by the RAB, and in total, 159 functions were the seismic forces for the two earthquakes under analysis.

As a final remark, for the nonlinear analysis, 27 cases of nonlinear dynamic analysis defined for the Mesa de los Santos earthquake and 26 cases for the Quetame earthquake, an initial nonlinear static case set at a distribution of 100% dead load and 25% live load, served as the initial condition for each of case of the nonlinear analysis.

3.Results

Based on the maximum displacements, it was possible to prepare demand maps according to the position of each one of the RAB stations, referred to the map of the city of Bogota for structural sway in the Y direction, and in the X direction too. The total computed structural sways using the root of the sum of the squares (SRSS) of each of the sways obtained in each X and Y direction were a better approach for total sway.

3.1 Sway according to a Mesa de los Santos Earthquake (2015)

3.1.1 5-story building.

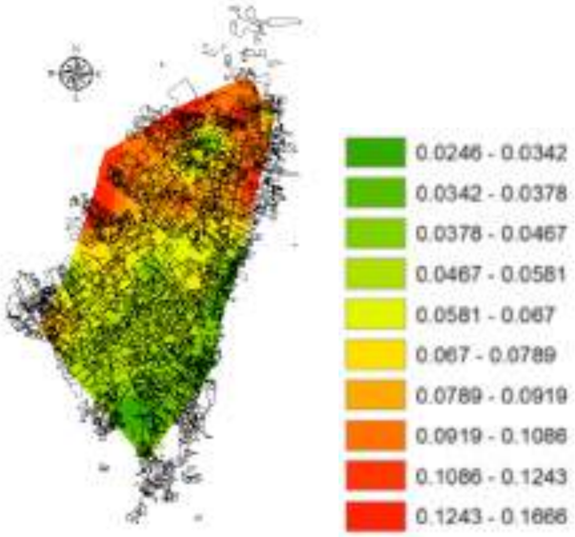

Figure 5. Map of maximum total sway, building designed for the Foothill – B spectrum

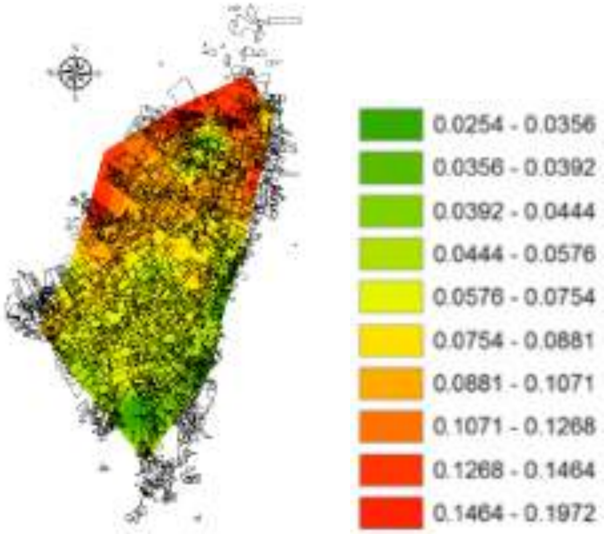

Figure 6. Map of maximum total sway, building designed for the Lacustrine – 500 spectrum

(Figure 5) shows the map with the distribution of the maximum total swat obtained for the 5-story building, according to the Foothill – B design spectrum. (Figure 6) shows the map with the distribution of the maximum total sway obtained for the 5-story building designed for the Lacustrine – 500 spectra. Here it is simple to see that the highest sway levels are in the north, northwest and northeast areas. These areas are: club el tiempo (CTIEM), parque la florida (CFLOD), universidad Corpas (CCORP), Escuela colombiana de ingeniería (CEING), universidad Agraria (CUAGR) and colonia escolar Usaquén (CUSAQ). Most of these stations are located in soft soils, except for the CUSAQ station, which is located in the transition between the Foothill – A and Lacustrine – 100 areas.

In the southern and southeastern areas of the city, low sway levels are observed for 5-story buildings at universidad Manuela Beltrán (CUNMA) and colegio de Kennedy (CCKEN) stations. This behavior may occur because unbraced steel moment resisting buildings must be significantly stiffened with high inertia sections in order to comply with sway requirements of NSR-10 (AIS, 2010).

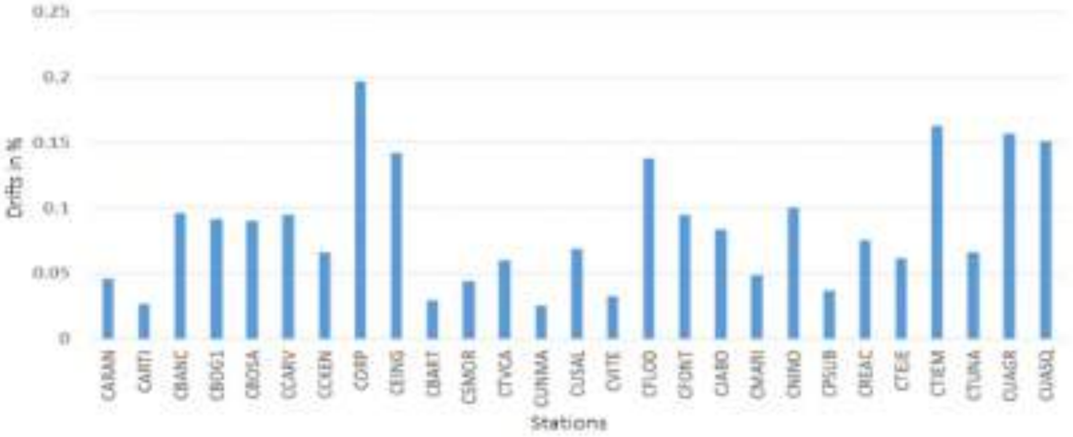

Figure 7. *Maximum total sway, 5-story building designed with the Lacustrine – 500 spectrum*

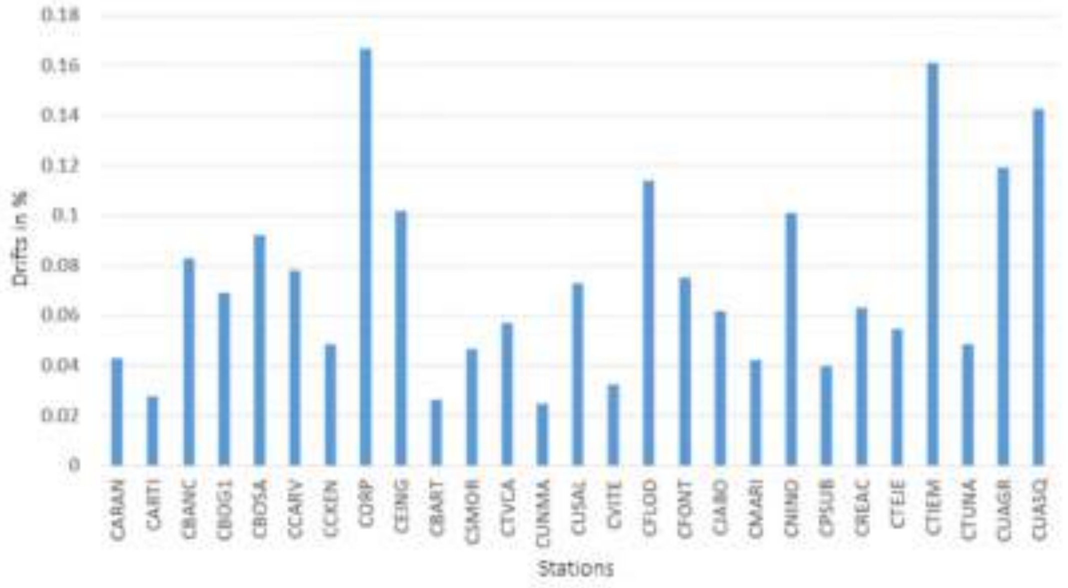

Figure 8. *Maximum total sway, 5-story building designed with the Foothill – B spectrum*

The stations that match the highest sway levels for the Quetame and Mesa de los Santos earthquakes for steel-designed buildings are club el tiempo *(CTIEM),* parque la florida *(CFLOD),* universidad Corpas *(CCORP),* Escuela colombiana de ingeniería *(CEING),* universidad Agraria *(CUAGR) and* colonia escolar Usaquén *(CUSAQ), as shown in (Figure 7) and (Figure 8).*

3.1.2 12-story building

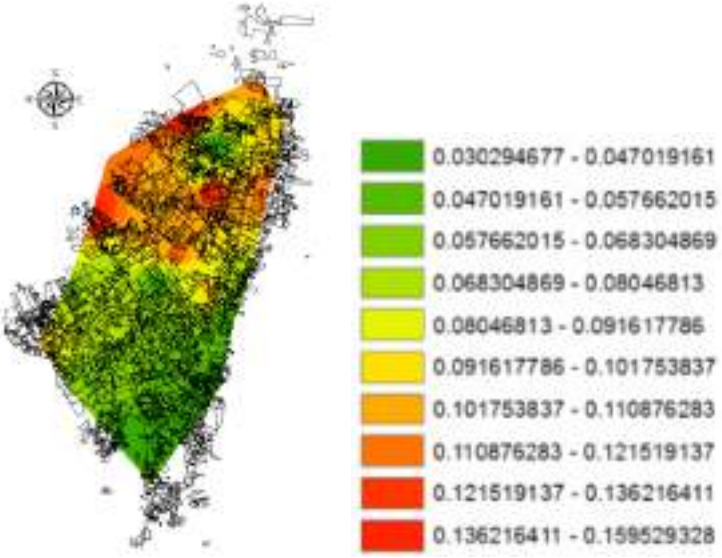

Figure 9. *Map of maximum total sway, building designed for the Foothill – B spectrum*

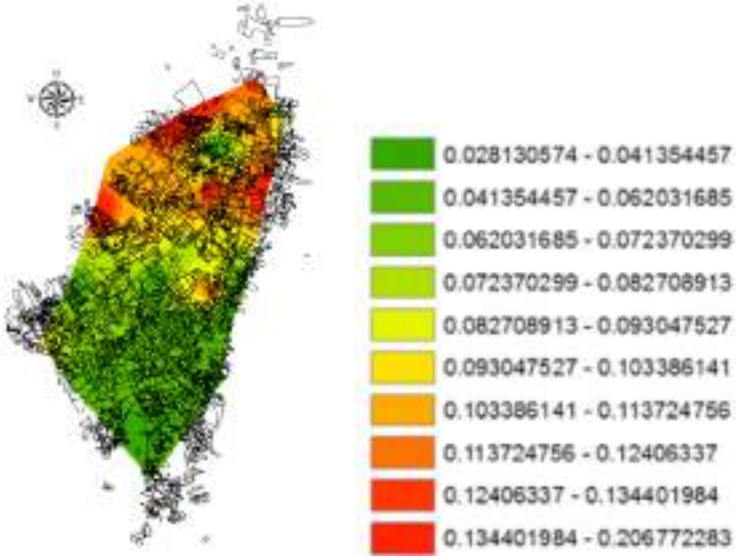

Figure 10. *Map of maximum total sway, building designed for the Lacustrine – 500 spectrum*

According to (Figure 9) and (Figure 10), the northern, north-western and north-eastern areas have the highest sway levels. These areas are located in soft soils, except for the CUSAQ station, which is located in the transition between the Foothill – A and Lacustrine – 100 areas.

In the south and southeastern area of the city, low sway levels are observed for 12-story buildings in universidad Manuela Beltrán (CUNMA) and colegio de Kennedy (CCKEN) stations. This behavior is similar to that shown in the 5-story buildings, where the areas with the highest sway levels continue to be the same in the city of Bogota, regardless of the number of stories built. They correspond to areas with soft soil strata or lacustrine areas, according to the geotechnical zonation map made for the seismic microzonation of Bogota, according to FOPAE (2010).

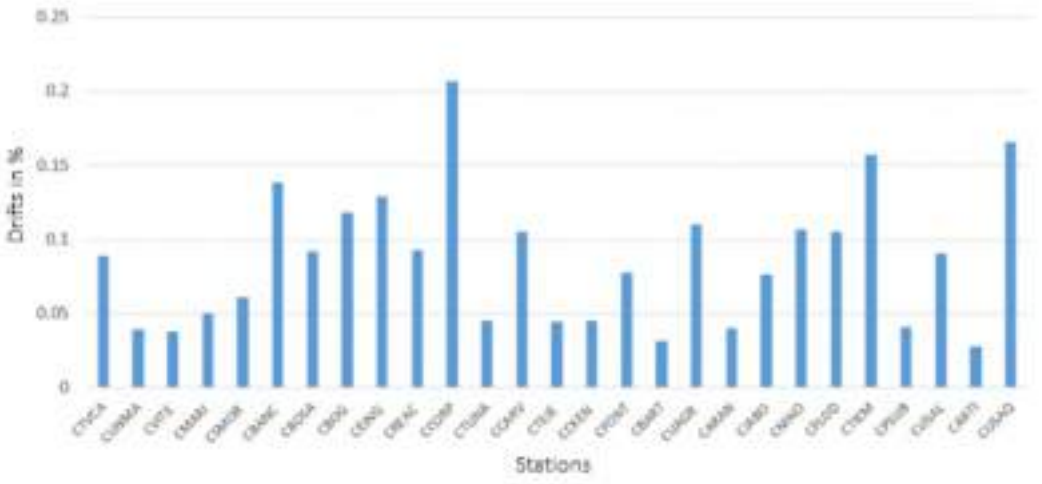

Figure 11. *Maximum total sways, 12-story building designed with the Lacustrine – 500 spectrum*

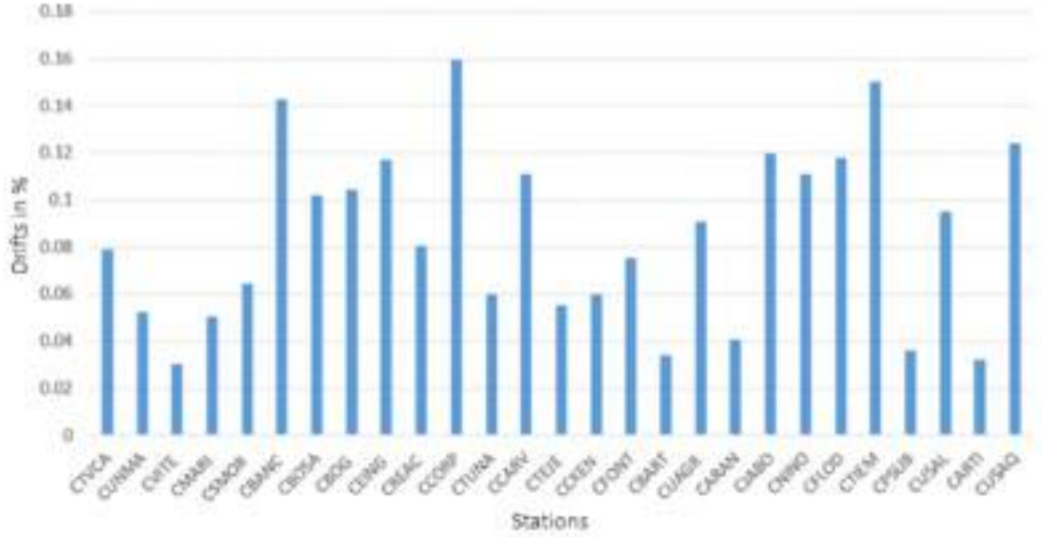

Figure 12. *Maximum total sways, 12-story building designed with the Foothill – B spectrum*

The stations with the highest levels in terms of sway percentage obtained from the nonlinear dynamic analysis are banco de la república (CBANC), clínica Corpas (CCORP) and club el Tiempo (CTIEMP) stations. They correspond to lacustrine soil areas depths between 150 to 400 meters. However, (Figure 11) and (Figure 12) show that all sways are within the limits established by NSR-10 (AIS, 2010), corresponding to sway levels below 1%.

3.1.3 20-story building

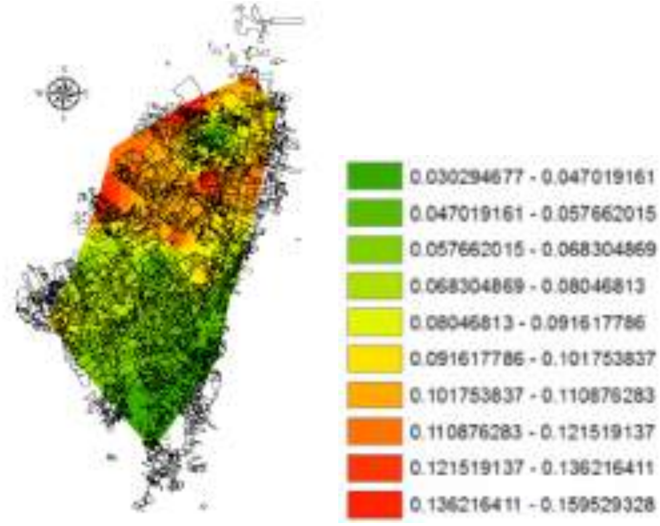

__Figure 13__. Map of maximum total sways, building designed for the Foothill – B spectrum

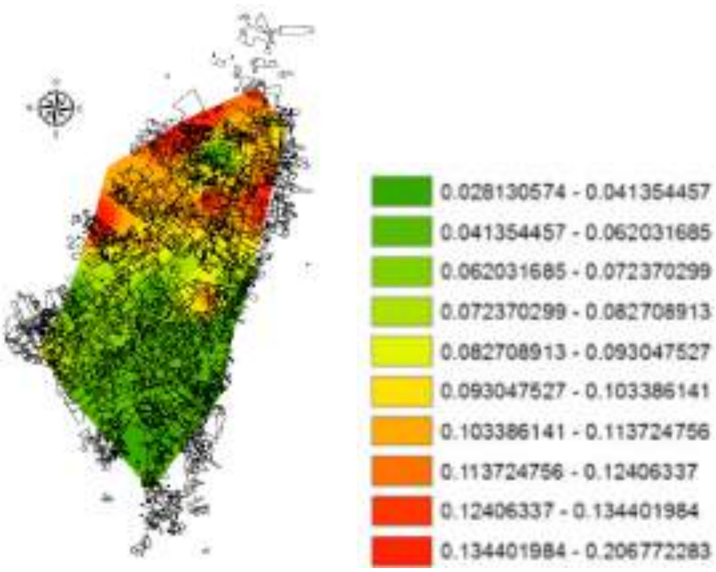

__Figure 14.__ Map of maximum total sways, building designed for the Lacustrine – 500 spectrum

The northern, north-western and north-eastern areas show the highest sway levels (similar to those in the 5 and 12-story buildings), and in the same way as in the 5 and 12-story buildings, the southern and southeastern areas of the city show low sway levels (see (Figure 13) for sways caused by the Foothill – B spectrum and (Figure 14) for sways caused by the Lacustrine – 500 spectrum).

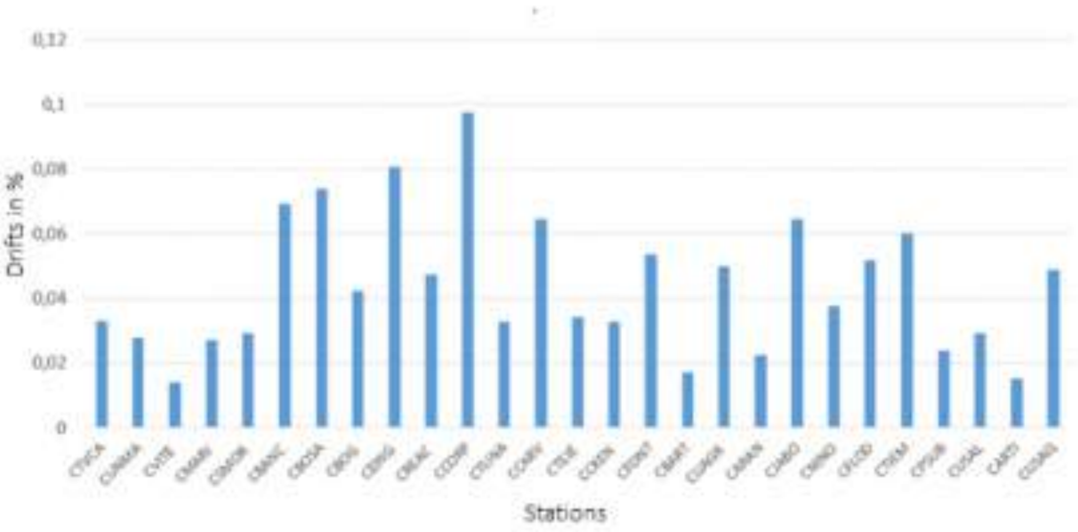

Figure 15. *Maximum total sways, 20-story building designed with the Lacustrine – 500 spectrum*

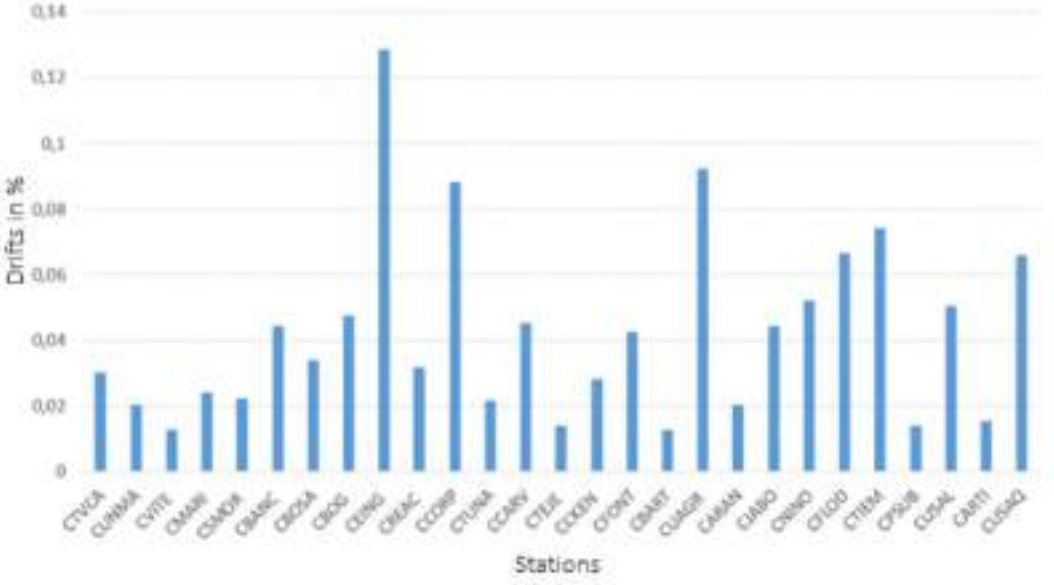

Figure 16. *Maximum total sways, 20-story building designed with the Foothill – B spectrum*

The stations recording the highest sway levels are those located where depths—according to FOPAE (2010)—are between 150 meters to 400 meters regardless of the designed spectrum used. The stations located in the eastern areas where depths are between 0 - 50 meters show lower sway levels in the sector from escuela de caballería to Marichuela. Despite the above, sways are low, and this can be explained by the fact that the higher steel structures were laterally braced to control lateral displacements see (Figure 15) and (Figure 16). Although lateral bracing function, increases material costs, it controls the total displacements in an efficient way.

3.2 Quetame earthquake (2008)

3.2.1 5-story building

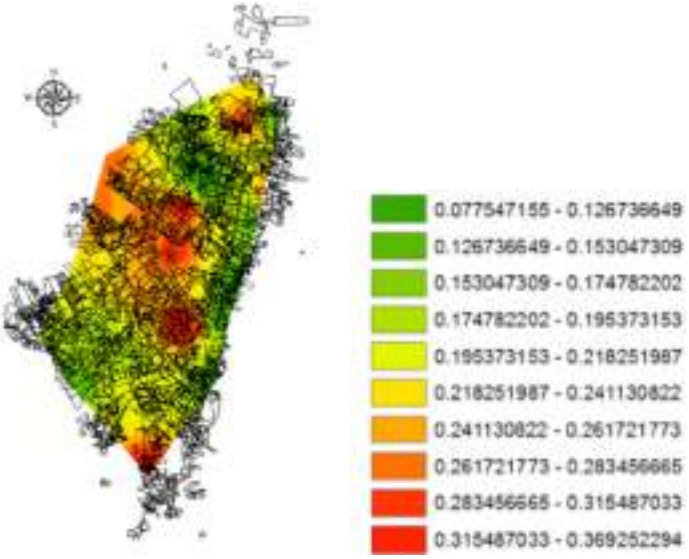

Figure 17. *Map of maximum total sways, building designed for the Foothill – B spectrum*

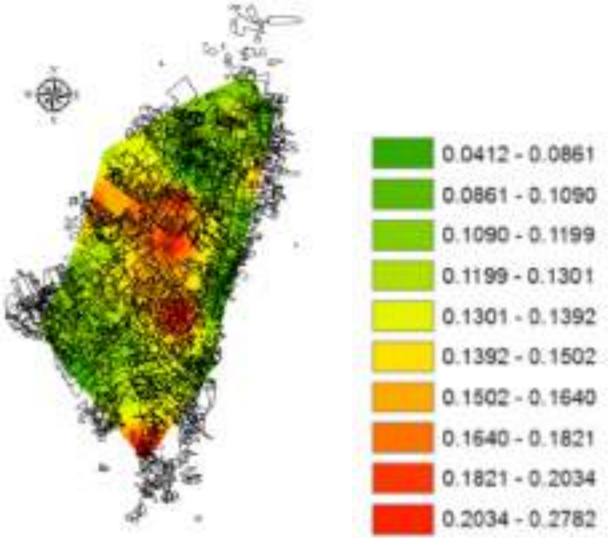

Figure 18. *Map of maximum total sways, building designed for the Lacustrine – 500 spectrum*

(Figure 17) shows that the highest sway levels happen at the southern, western and central areas of Bogota. Most of these areas are located in soft soils, except for the Usaquén *area, which transitions between the Foothill – A and Lacustrine – 100 areas. In contrast to (Figure 18), which shows that the northern, southern, western and central areas of Bogota have the highest sway levels, just as in the building designed with the Lacustrine – 500 spectra, the only area that is not in soft soil is* Usaquén *(north-eastern area).*

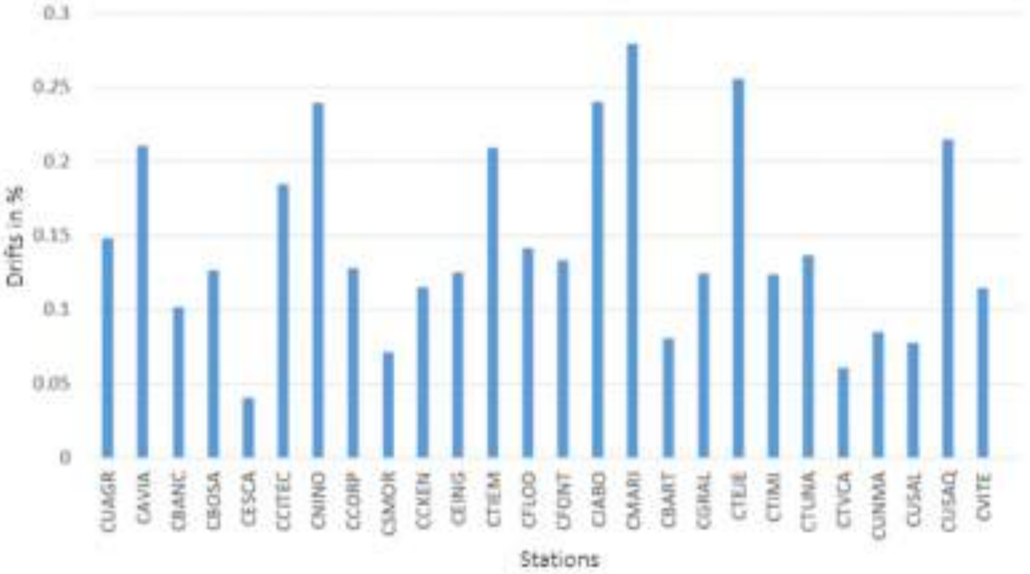

Figure 19. *Maximum total sways, 5-story building designed with the Lacustrine – 500 spectrum*

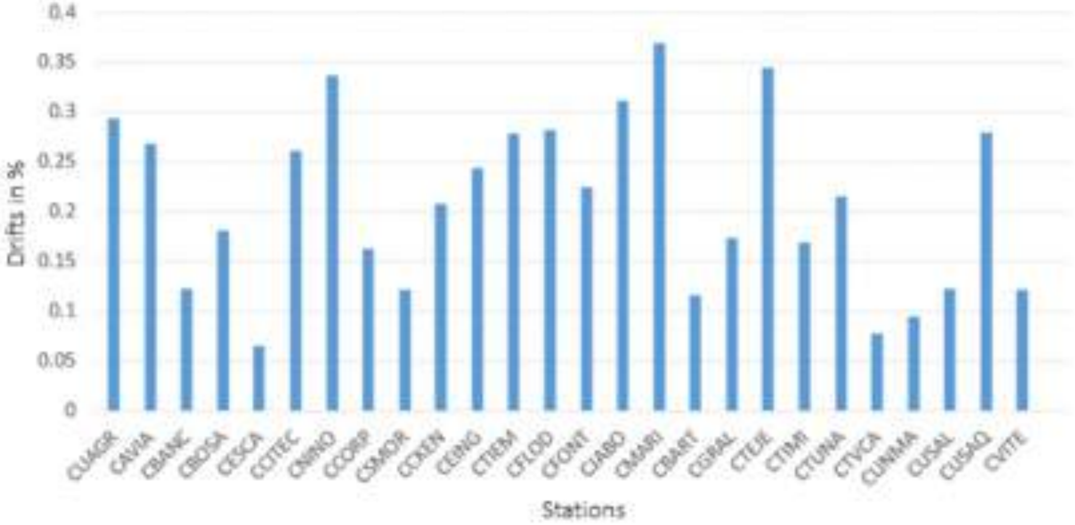

Figure 20. *Maximum total sways, 5-story building designed with the Foothill – B spectrum*

For the 5-story buildings, designed under the Lacustrine – 500 and Foothill – B spectra, the stations with the highest sway levels are bomberos la Marichuela (CMARI), club el tiempo (CTIEM), Centro de estudios del niño (CNINO), jardín botánico (CJABO), Escuela colombiana de ingeniería (CEING), Avianca (CAVIA) and colonia escolar Usaquén (CUSAQ), as available in (Figure 19) and (Figure 20). The effect of higher sway demands could be due to the higher lateral force used for the design of the structure before being subjected to the different seismic signals used in this study.

3.2.2 12-story building

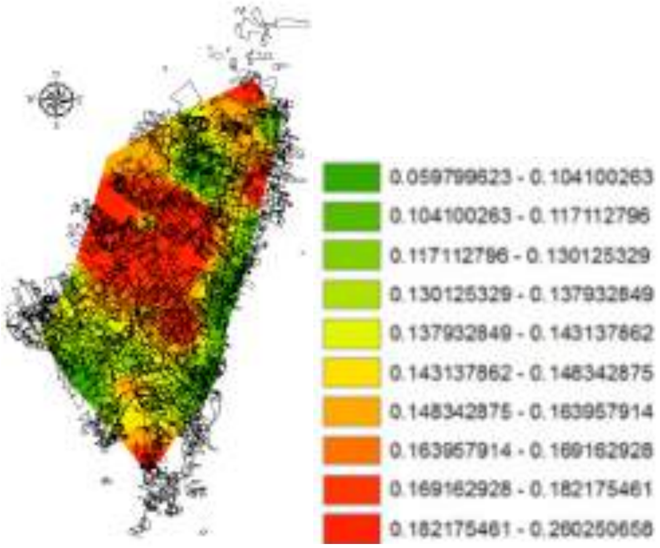

Figure 21. *Map of maximum total sways, building designed for the Foothill – B spectrum*

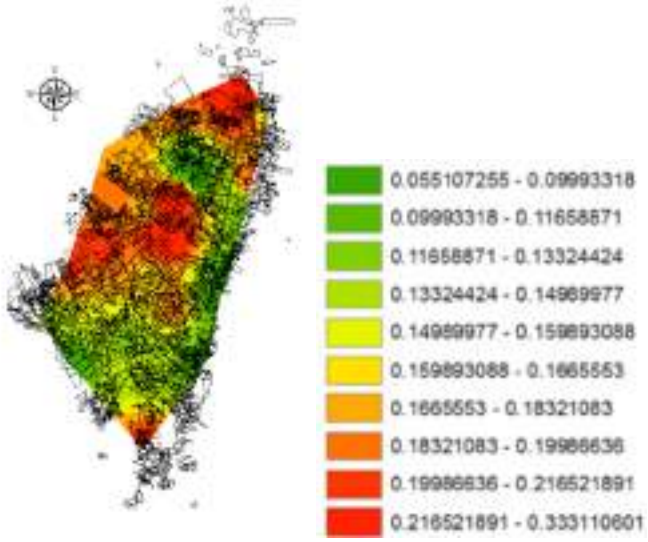

Figure 22. *Map of maximum total sways, building designed for the Lacustrine – 500 spectrum*

(Figure 21) shows the central area of Bogota having the highest sway levels, from west to east between aeropuerto el Dorado and la carrera 30, and from north to south between calle 80 and avenida primero de mayo. The southern area, where bomberos la Marichuela (CMARI) station is located in the south of the city, has similar sway levels to the central area along with colonia escolar Usaquén (CUSAQ) station, even though it is located in a transition area of the Foothill – A and Lacustrine – 100 areas. The same occurs in (Figure 22), which has the same distribution of sway levels, although designed for a different spectrum.

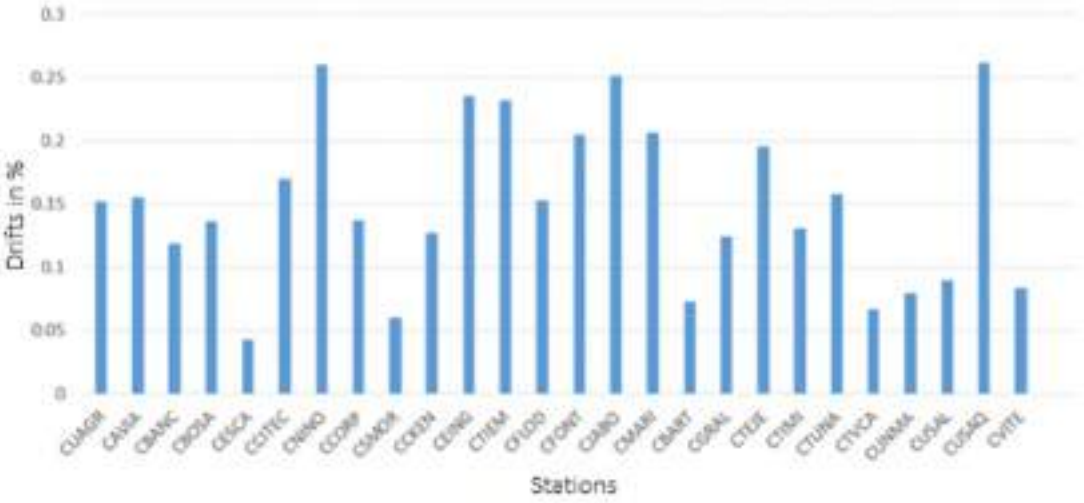

Figure 23. *Maximum total sways, 12-story building designed with the Lacustrine – 500 spectrum*

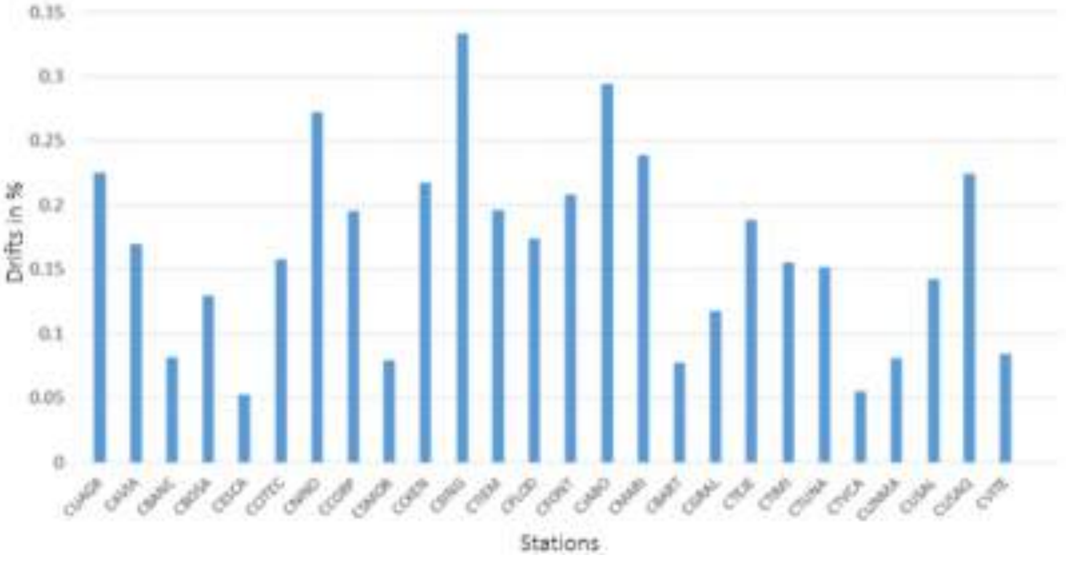

Figure 24. *Maximum total sways, 12-story building designed with the Foothill – B spectrum*

The stations with the highest sway levels are Escuela Colombiana de Ingeniería (CEING), Colonia escolar Usaquén (CUSAQ), Clínica del niño (CNINO) and Jardín botánico (CJABO) for both design spectra, as shown in (Figure 23) and (Figure 24).

3.2.3 20-story building

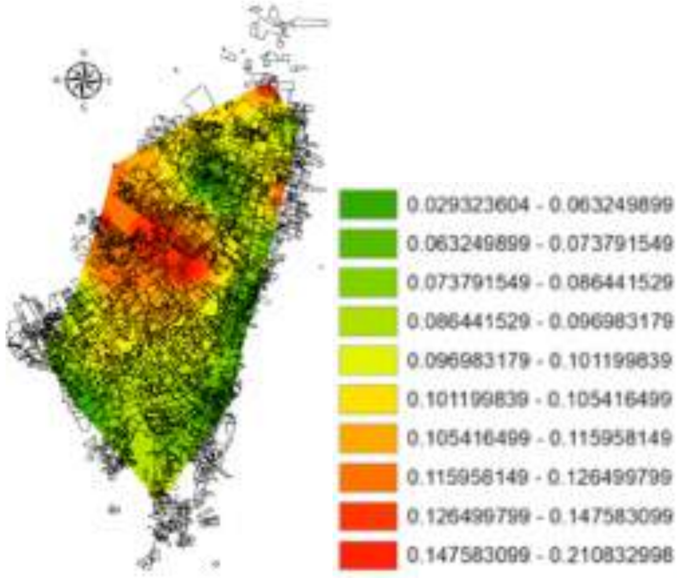

Figure 25. *Map of maximum total sways, building designed for the Foothill – B spectrum*

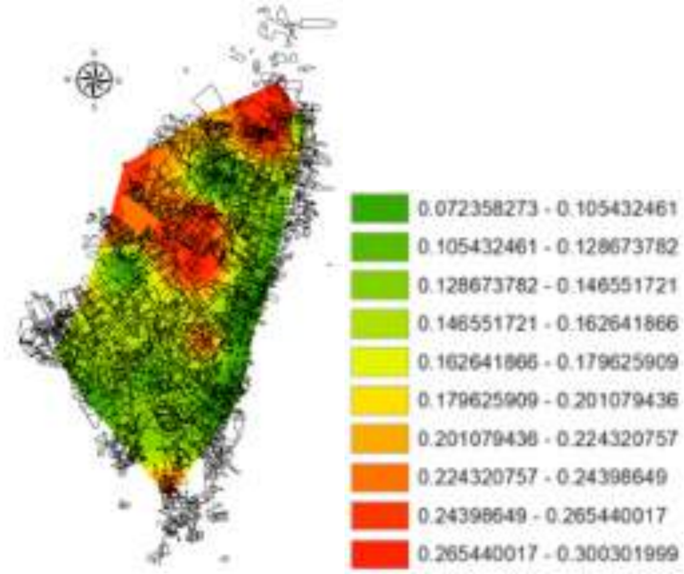

Figure 26. *Map of maximum total sways, building designed for the Lacustrine – 500 spectrum*

(Figure 25) and (Figure 26) show the center area of Bogota having the highest sway levels, followed by the north and northwest areas.

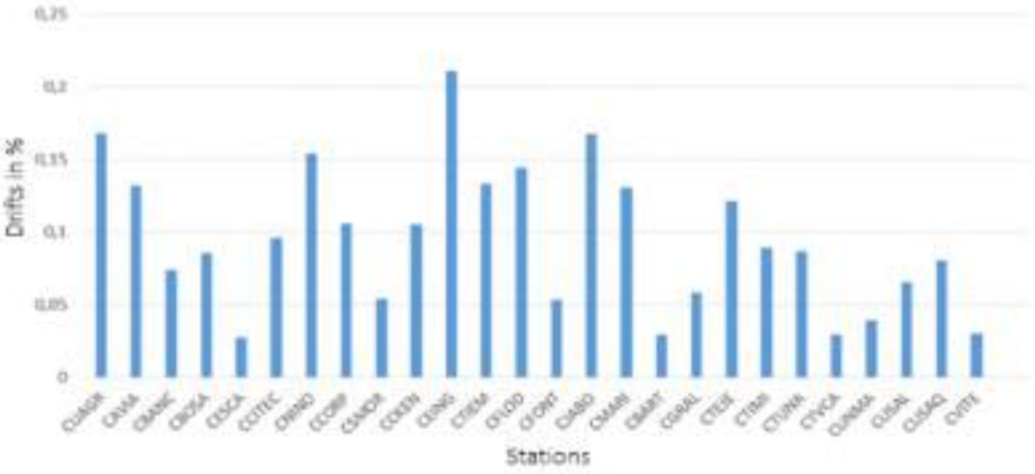

__Figure 27.__ Maximum total sways, 20-story building designed with the Lacustrine – 500 spectrum

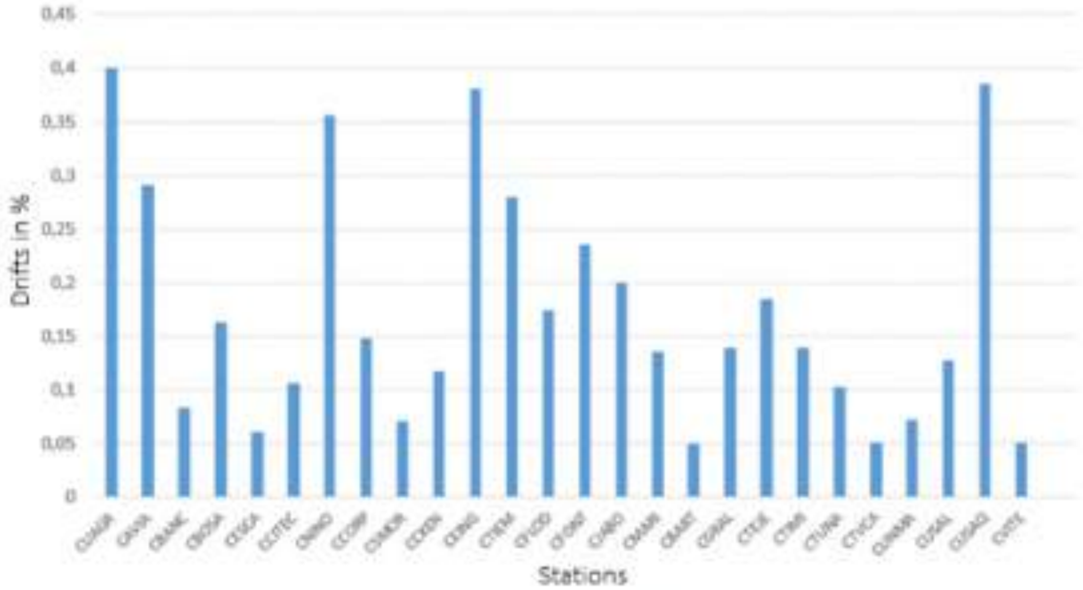

__Figure 28.__ Maximum total sways, 20-story building designed with the Foothill – B spectrum

The maximum sway levels presented in the 20-story building see (Figure 27) and (Figure 28) subjected to the Mesa de los Santos earthquake are reflected in the stations of universidad Agraria (CUAGR), Clínica del Niño, Escuela Colombiana de Ingenieros and Usaquén for the design having the Foothill spectrum as seismic force. The stations for the building designed with the Lacustrine – 500 spectra are universidad Agraria, Clínica del Niño, Escuela Colombiana de Ingenieros and Jardín Botánico.

The lowest sway levels for the building designed with the Lacustrine – 500 spectra and for the building designed with the Foothill – B spectrum are Tanques de Vitelma (CVITE), colegio San Bartolomé (CBART) and Escuela Colombiana de Ingeniería (CESCA), which are located in the eastern hills depth is between 0 to 50 meters approximately, according to the layer depth maps established by FOPAE, (2010).

3.3 Damage and inelasticity

The linear dynamic analysis led to determine which elements suffered any possible plastic damage. Therefore, it was essential to establish whether the elements showed any type of inelasticity, especially for the seismic time histories under study, as these events are far from reaching the magnitude of the any design earthquake. No hinging happened for the 5 and 12-story buildings for neither the Quetame nor Mesa de los Santos earthquakes, i.e., the four buildings, two for the Lacustrine – 500 spectra and two for the Foothill – B spectrum, behaved within the linear range, without permanent deformations. However, for typical 20-story buildings subjected to the Quetame seismic event see (Figure 29) and (Figure 30), column hinging took place at the upper floors.

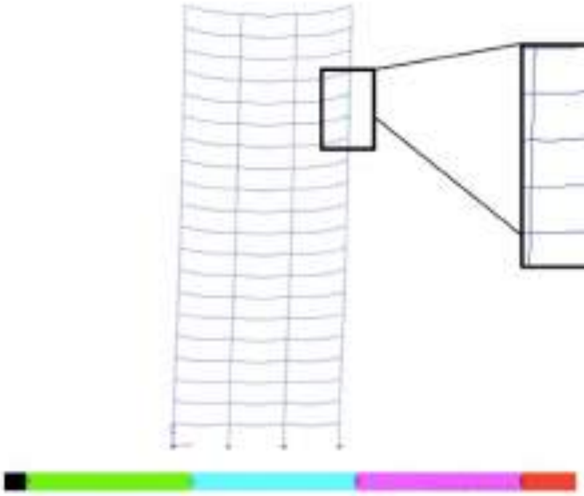

Figure 29. *Hinged frame in 20-story building for the Mesa de los Santos earthquake, C-JABO station, and designed with the Foothill – B spectrum*

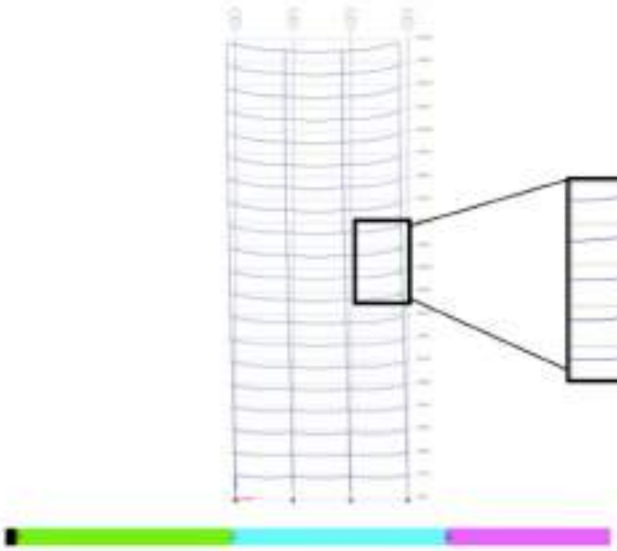

Figure 30. *Hinged D Frame in 20-story building for the Quetame earthquake, C-EING station, and designed with the Lacustrine – 500 spectrum*

The 20-story buildings showed hinging only from section yielding, i.e., inelasticity away from high energy dissipation.

(Table 8) shows a summary of the inelastic behavior for the 20-story buildings. It is important to state that 23% of hinging (hinged elements) happened for the Mesa de los Santos earthquake, and 77% of hinging (hinged elements) for the Quetame earthquake.

Table 8. *Hinging in 20-story buildings*

Reported Inelasticities for 20-story Buildings				
Case	***Hinging amount***	***Earthquake***	***Spectrum***	***Damage level***
C-JABO	*2*	*Mesa de los Santos*	*Lacustrine*	*Section yielding*
C-EING	*5*	*Quetame*	*Foothill*	*Section yielding*
C-NINO	*2*	*Quetame*	*Foothill*	*Section yielding*

3.4 Comparison with concrete buildings

It is interesting to establish a comparison between the results of the structural designs (controlling sways) obtained in the present study with results available for a similar exercise, however using reinforced concrete as the main design material of the structures under study (Ruiz et al., 2012). These results are comparable since it was possible to implement the same structural floor plan, story height and same nonlinear analysis methodology. Also, a comparison parameter can be established between the weight required to build a functional structure in concrete with that in steel. This is reported in the last column of (Table 9).

Table 9. *Total weight of buildings designed in steel and their comparison with structures of the same height designed in reinforced concrete*

Building height	***Unit***	***Weight***	***Design spectrum***	***Material***	$W_{steel} / W_{concrete}$
5 stories	*kN*	*29996.54*	*Lacustrine*	*Steel*	*0.70*
5 stories	*kN*	*42821.86*		*Concrete*	
5 stories	*kN*	*29616.40*	*Foothill*	*Steel*	*0.62*
5 stories	*kN*	*47584.55*		*Concrete*	
12 stories	*kN*	*69784.03*	*Lacustrine*	*Steel*	*0.53*
12 stories	*kN*	*131622.05*		*Concrete*	
12 stories	*kN*	*69677.09*	*Foothill*	*Steel*	*0.53*
12 stories	*kN*	*130858.61*		*Concrete*	
20 stories	*kN*	*122667.07*	*Lacustrine*	*Steel*	*0.39*
20 stories	*kN*	*319463.05*		*Concrete*	
20 stories	*kN*	*122101.38*	*Foothill*	*Steel*	*0.46*
20 stories	*kN*	*262515.75*		*Concrete*	

The nonlinear behavior of steel structures compared to concrete structures is better from the point of view of the generation of hinges in structural elements, part of the seismic resistance system, since only nine (9) yielding hinges formed in the 20-story buildings: 7 for the Quetame earthquake event, designed with the Lacustrine spectrum and 2 for los Santos earthquake event for the building designed using the Foothill - B spectrum. No hinges reported neither for the 5 nor the 12-story buildings unlike the buildings designed in concrete, which according to (Ruiz et al., 2012), allowed the formation of a total of 105 hinges for the 5-story building, 154 hinges for the 12-story building and 676 hinges for the 20-story building. This sums up to 935 hinges. In other words, 99.1% less inelastic excursions happened in steel buildings compared to those in concrete buildings.

Regarding the total structural weight, there are differences from 30% to 68%, with steel buildings being lighter, with lower damage levels in structural elements and complying with the maximum sway limits required by NSR-10 (AIS, 2010). In structures with a higher number of levels, the use of concentric bracing elements to control sway has a similar or lower cost than the cost of a structural moment frame solution (cost per square meter) to control sway, mainly due to the size of the columns. This is similar to what was reported in a recent study of sway cost control based on different structural alternatives available (Barbagallo et al., 2021). In general, the aforementioned analysis suggests that steel buildings, as they are lighter and have better seismic behavior, can generate lower foundation costs as the height of the building increases, since the greater the height, the decrease in weight increases without sacrificing performance in case of a seismic event. Also, although it was not part of this study, it can be inferred that if the structure is lighter for the same level of functionality, this characteristic will also be transferred to the foundation design, making the overall construction costs of the building lower too.

4. Conclusions

The stations with the highest sway levels in the 5, 12 and 20-story buildings for the Mesa de los Santos earthquake, in both design spectra, are Universidad Corpas (CCORP), Escuela Colombiana de Ingeniería (CEING), Colonia Escolar Usaquén (CUSAQ), Club el Tiempo (CTIEMP) and Universidad Agraria (CUAGR).

The stations that generated higher sway levels in the 5, 12 and 20-story buildings, for the Quetame earthquake, in both design spectra, were Bomberos la Marichuela (CMARI), Club el Tiempo (CTIEM), Centro de Estudios del Niño (CNINO), Jardín Botánico (CJABO), Escuela Colombiana de Ingeniería (CEING), Avianca (CAVIA) and Colonia Escolar Usaquén (CUSAQ).

No hinges formed in any of the 5 and 12-story buildings subjected to the Quetame earthquake. Therefore, it can be concluded that since none of the elements yielded, the structures did not exceed the linear range, presenting an elastic behavior. Also, there was no tearing of the connections designed for the expected earthquake occurrence under the Foothill – B and Lacustrine – 500 spectra, which correspond to the highest and lowest acceleration spectra of Decree 523 of 2010, respectively.

Hinges were only available for the 20-story buildings. However, they reached a damage level only of section yielding, which leads to immediate use of the buildings after the occurrence of an earthquake, i.e., the damage to structural elements does not consider any severity or effects with the event of an aftershock.

The areas that presented the highest levels of maximum total sways for Mesa de los Santos and Quetame earthquakes of 2015 and 2008 were the central, north-eastern and north-western areas in the city of Bogota, approximately from north to south between calle 80 and Avenida Primera de Mayo. The sector with the highest sway levels for 5, 12 and 20-story buildings is from east to west between Carrera 30 and aeropuerto el Dorado.

Finally, the comparison of the total weights of the structure (concrete vs. steel) and its structural behavior suggests that steel structural system is a more economical competitive system, with lower foundation system requirements, compared to concrete structures of the same size and architectural geometry.

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