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COMPARATIVE ANALYSIS OF SEISMIC DESIGN FORCES IN DIAPHRAGMS OF PERUVIAN RC BUILDINGS

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Abstract

The last major earthquakes, such as the 1964 Alaska earthquake, caused severe damage in floor rigid diaphragms of reinforced concrete buildings, consequently, many structures presented a detrimental seismic-resistant behavior [1]. It is widely known that the major functions of a diaphragm are: the transmission from lateral loads to the vertical resisting elements, the support for the gravity loads, the force transference through the diaphragm, among others [2][3]. Thus, it is necessary to analyze the seismic forces in the diaphragm for the floor element design.

Five typical Peruvian buildings, made of reinforced concrete (RC), are analyzed using nonlinear time-history simulations under Peruvian earthquakes records, which were obtained from the database of the Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) and the Geophysical Institute of Peru (IGP).

Absolute accelerations are considered to be proportional to seismic diaphragm forces because of the relationship between them is given by the mass. Therefore, the main focus of this study is the comparative analysis of absolute diaphragm accelerations obtained by seismic analyses on the five beforementioned buildings. Furthermore, the location of the main inflection points of the absolute acceleration distribution in the percentage of the height is identified for each building.

Finally, a normalization with respect to maximum base acceleration is carried out, in order to obtain a tri-linear relationship within the region limited by the mean plus or minus one standard deviation. This tri-linear relation represents a first proposal for the estimation of seismic forces so that the diaphragms and their elements are well-designed.

Keywords: Diaphragm, non-linear time-history analysis, Response-Spectrum Analysis.

1. Introduction

The typical seismic-resistant analysis estimates horizontal forces in the diaphragm based on Seismic Linear Static Analysis, as well as the linear spectral modal analysis, so that, each of these forces is considered for the diaphragm design. Furthermore, they are used as design forces, meaning that they are reduced forces. However, these forces may differ from a Nonlinear Structural Analysis [1]. These effects are reviewed and considered.

Some methodologies were proposed to assess this issue, for instance, Los Angeles Tall Buildings Structural Design Council (LATBSDC) funded in 1988 to provide a space for discussion of issues related to the design of tall buildings, has published the 2011 version of the document "An Alternative Procedure For Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region," it presents provisions for modeling rigid diaphragms [4]. Currently, this document is in its 2017 version, which contains detailed information of diaphragm modeling in high-rise buildings [5]. Moreover, the current ACI standard 318-19 "Building Code Requirements for Structural Concrete" and the Peruvian Standard E.060 "Concreto Armado" (Reinforced Concrete Design) present minimum requirements for the design of diaphragms (chapter 18 and 21 respectively) [6][7]. Another point worth noting is ASCE 7-16 "Minimum Design Loads and Associated Criteria for Buildings and Other Structures" where an alternative methodology is proposed to obtain forces in the diaphragm [8].

In Peru, the Peruvian Standard E.030 "Diseño Sismorresistente" (Earthquake-Resistant Design) allows the use of rigid diaphragms but does not present a methodology for obtaining forces in diaphragms [9]. Due to this gap, the National Service of Normalisation, Training, and Research for the Construction Industry (SENCICO) has conducted researches to assess the structural diaphragm behavior in high-rise and mid-rise

Peruvian buildings [1], these studies emphasize that considerable accelerations appear just under 80% of the height building, nonetheless, further investigation of non-linear behavior need to be carried out. Therefore, a methodology for Peruvian RC Buildings which considers the effects of Nonlinear Structural Analysis in diaphragm performance is necessary to contribute to the continual updating of information concerning structural engineering in Peru and worldwide.

In this article, five typical Peruvian RC buildings are analyzed using nonlinear time-history analyses under Peruvian earthquakes records obtained from the database of Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) and the Geophysical Institute of Peru (IGP). As a result of this study, maximum absolute accelerations are obtained and compared for each earthquake record in order to set a tri-linear relationship with respect to height percentage.

2. Description of Peruvian Buildings of RC

Five (05) types of structures are analyzed using Nonlinear Time – History Analysis under 03 seismic historical records of Peru.

1ST Peruvian Building

The 1ST Peruvian Building is a structure of 11 stories and 3 basements. The structural system is RC frame with shear walls (concrete shear walls are the main system according to the base shear). The building does not have structural irregularities according to Peruvian Standard.

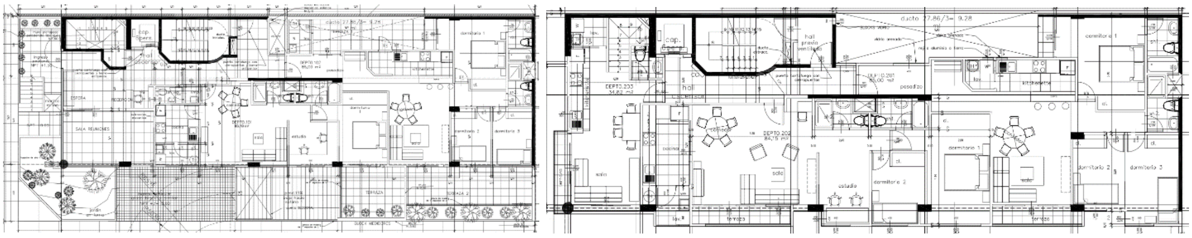


Fig. 1 – Architectural Plan: First floor (left) and Typical floor (right) of the 1ST Peruvian Building

Fig. 2 – Front Elevation (left) and Transversal Section (right) of the 1ST Peruvian Building

2ND Peruvian Building

The 2ND structure is a 10-story building. The structural system is RC frame with shear walls (concrete shear walls are the main system according to the base shear). The building does not have structural irregularities according to Peruvian Standard.

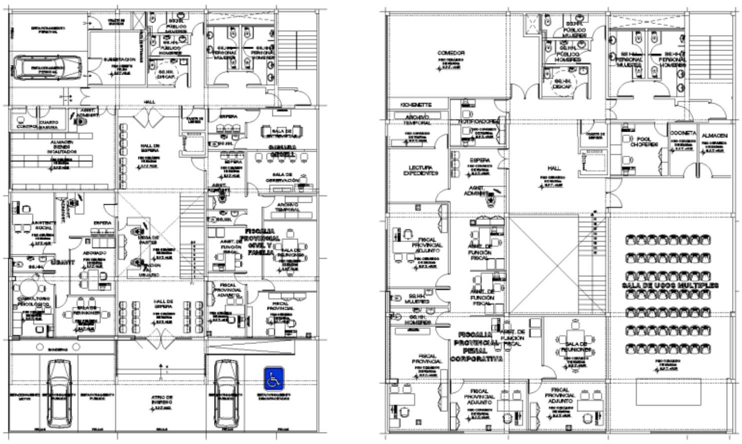


Fig. 3 – Architectural Plan: First floor (left) and Typical floor (right) of the 2ND Peruvian Building

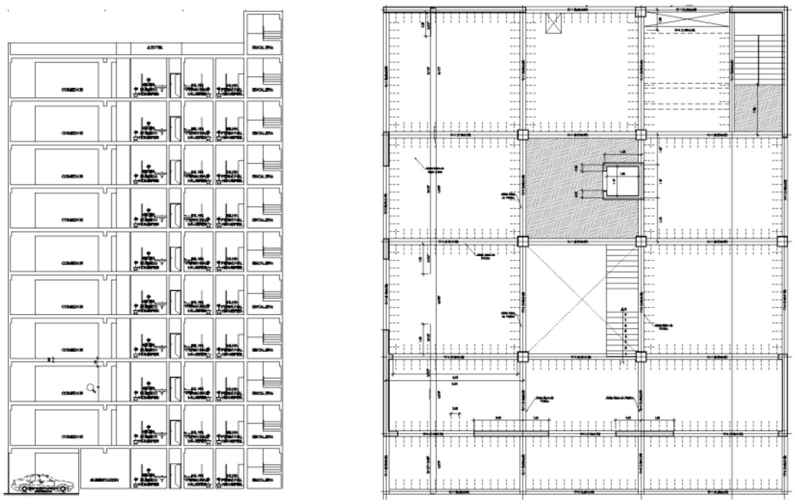


Fig. 4 – Transversal Section (left) and Structural Plan: Typical floor of the 2ND Peruvian Building

3RD Peruvian Building

The 3RD Peruvian Building is a structure of 18 stories and 4 basements. The structural system is RC frame with shear walls (concrete shear walls are the main system according to the base shear). The building has structural irregularities according to Peruvian Standard.

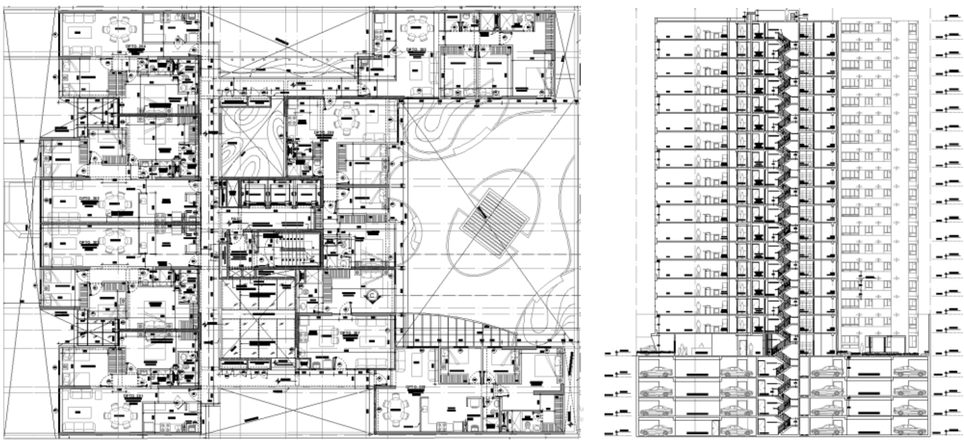


Fig. 5 – Architectural Plan: Typical floor (left) and Longitudinal Section (right) of the 3RD Peruvian Building

4TH Peruvian Building

The 4TH Peruvian Building is a structure of 17 stories and 8 basements. The structural system is RC frame with shear walls (concrete shear walls are the main system according to the base shear). The building has structural irregularities according to Peruvian Standard.

Fig. 6 – Architectural Plan: Typical floor (left) and Transversal Section (right) of the 4TH Peruvian Building

5TH Peruvian Building

The 5TH Peruvian Building is a structure of 15 stories and 4 basements. The structural system is RC frame with shear walls (concrete shear walls are the main system according to the base shear). The building has structural irregularities according to Peruvian Standard.

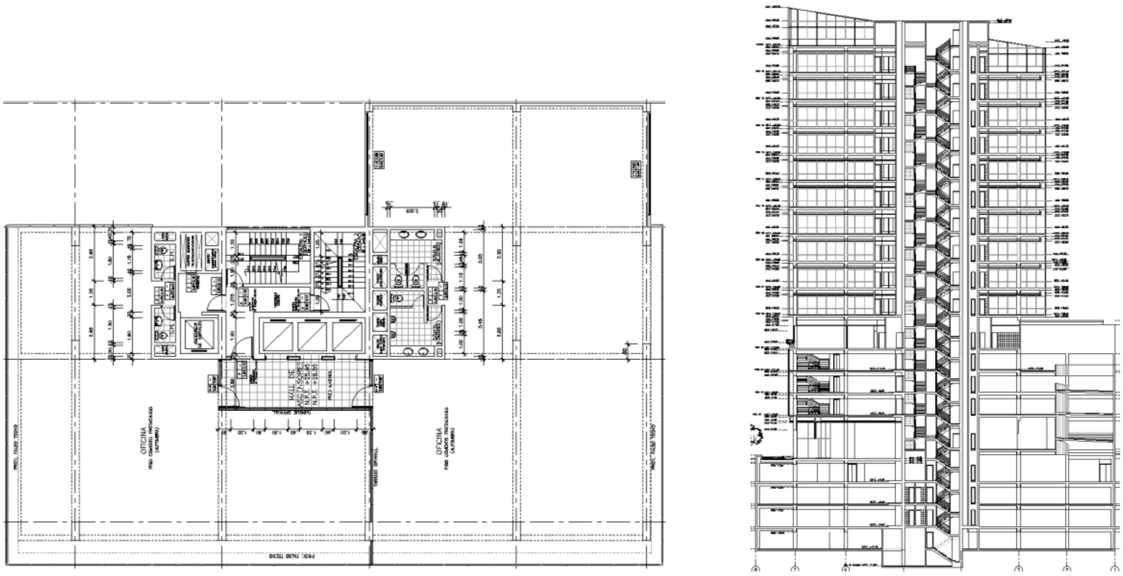


Fig. 7 – Architectural Plan: Typical floor (left) and Longitudinal Section (right) of the 5TH Peruvian Building

3. Ground motion selection and spectral scaling

The seismic records considered in this study were obtained from the accelerograph station "Parque de la Reserva" located over a rigid stratum in Lima district. This station has registered three main ground motions for Lima in 1966, 1970 and 1974, these earthquakes have similar parameters like seismic magnitude, focal depth, and source mechanism. It is worth pointing out that they were considered for defining response design spectra published in the Peruvian Standard E.030.

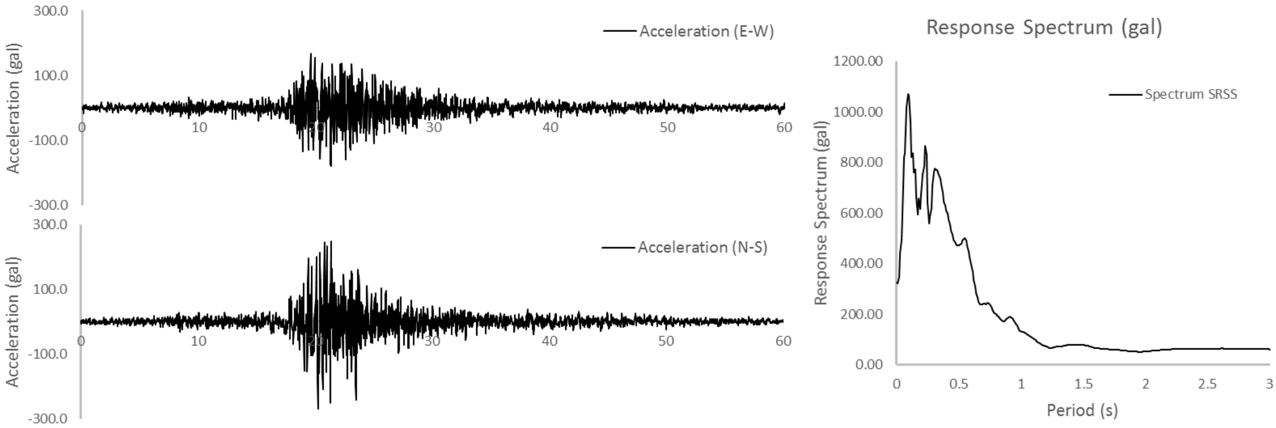


Fig. 8 – Ground motion and Response Spectrum obtain from PQR station for 1966 Earthquake.

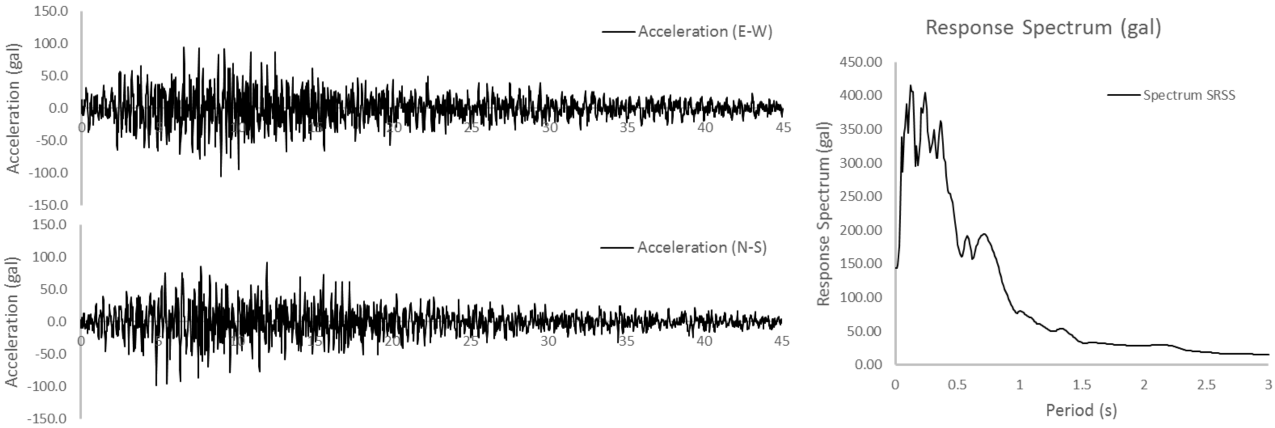


Fig. 9 – Ground motion and Response Spectrum obtain from PQR station for 1970 Earthquake.

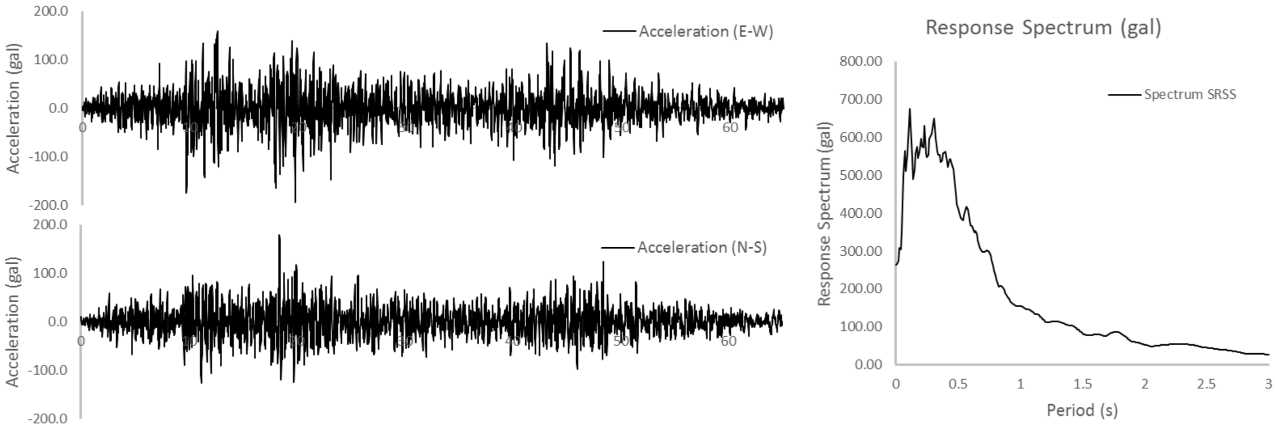


Fig. 10 – Ground motion and Response Spectrum obtain from PQR station for 1974 Earthquake.

Table 1 – Main earthquake parameters of selected ground motions.

RECORD	DATE	MAGNITUDE	DEPTH	PGA (gal)	
				EW	NS
1966	17-Oct-66	8.1 Mw	24.00 km	180.56	268.24
1970	31-May-70	6.6 mb	64.00 km	105.05	97.81
1974	3-Oct-74	6.6 mb	13.00 km	194.21	180.09

The seismic records are processed by doing baseline correction and passband filters. Each record has been scaled in both horizontal components (East and North) so that the square root of the sum of the square acceleration of each component are higher than the design spectrum for a specific period rank, as the E030 standard regulates.

4. Structural criteria and settings

Model, Analysis, and Response of the structures were performed using criteria and settings, as follows:

- The basement was not considered, it is to say, the first floor is modeled with a fixed base.
- Stiffness properties were assigned to slabs, it is to say, the diaphragm is modeled as semirigid.
- Each slab is considered as a shell element with an elastic material behavior.
- Numerical simulations were computed under three Peruvian earthquake records.
- Bidirectional seismic analysis is performed. The E-W direction is oriented to the X-X axis of the structures and the N-S direction coincides with the Y-Y axis.
- Absolute accelerations are considered to be proportional to seismic diaphragm forces because of the relationship between them is given by the mass. It is worth pointing out that in this study only diaphragm accelerations are analyzed.
- Diaphragm accelerations were obtained by nonlinear time-history analyses and then are compared with other records.

5. Response of Structures

Several numerical simulations throw different results however some patterns are identified, as follows:

- In diaphragm acceleration distributions two inflection points can be distinguished, the first one is found lower the middle height and the other one upper the middle height.
- The maximum absolute acceleration estimated at the building top is more than 2.0 times the maximum acceleration at the base.
- In most cases, diaphragm accelerations lie within the region limited by one standard deviation of the mean.

Detailed information of the building results is explained bellow, note that every simulation outcome mainly depends on the input motion, the structural modal parameters and the structural nonlinear behaviour.

Regular Peruvian Buildings

For the first two buildings, maximum absolute accelerations were obtained in the top floor (approximately more than 3.0 times the maximum base acceleration) and the acceleration varies along with the building height as Fig. 11 and Fig. 12 depicts. A soft variation can be identified in these figures, however, there are abrupt variations in height due to the nonlinear behavior. See that the mean shape could be fitted to a polynomial curve.

In the first structure, the mean shape is significative different for both axes because of the structural element distribution, while in the second one, mean shapes are similar for both axes. The mean curves are also shown in Fig. 11 and Fig. 12 as black dashed lines, likewise, a region limited by one standard deviation of the mean is enclosed by gray lines in order to show the result variation graphically.

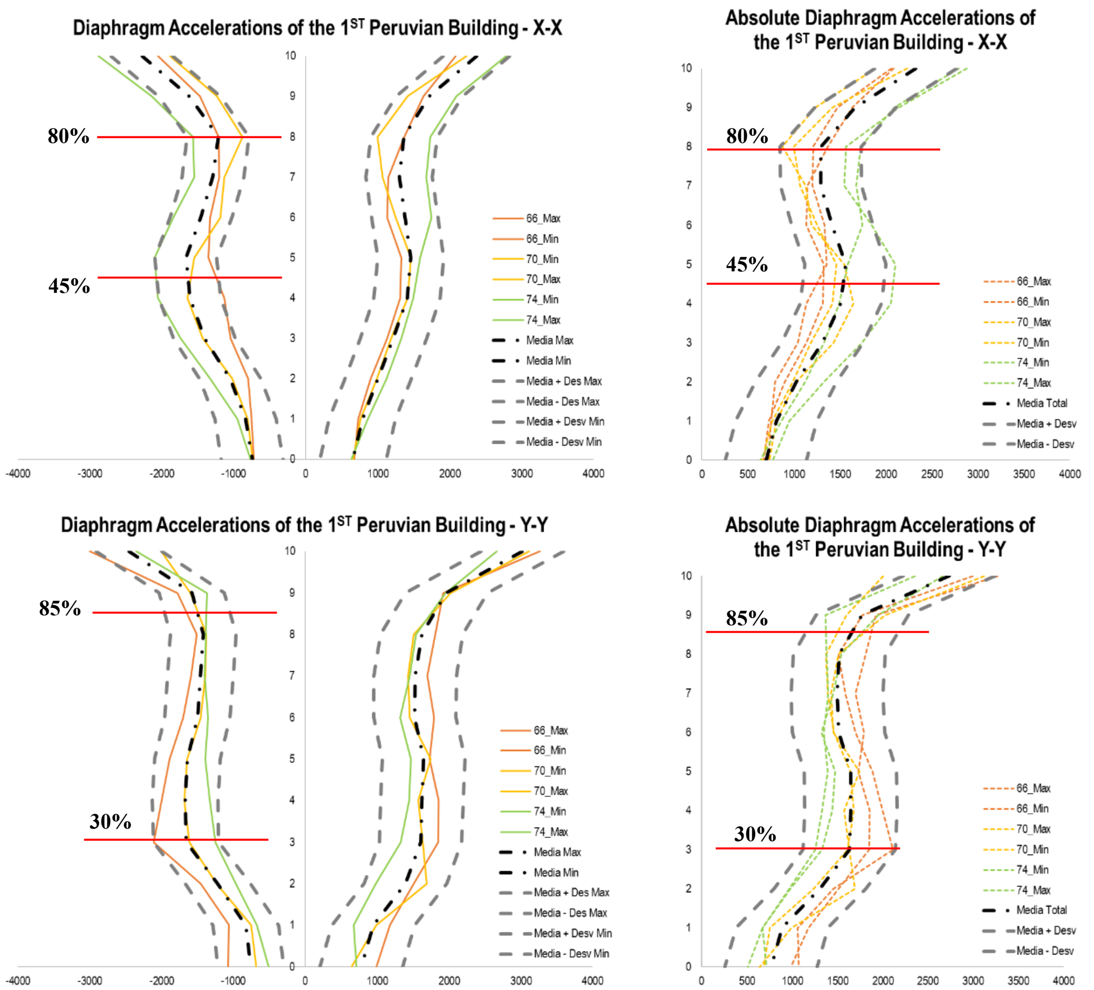
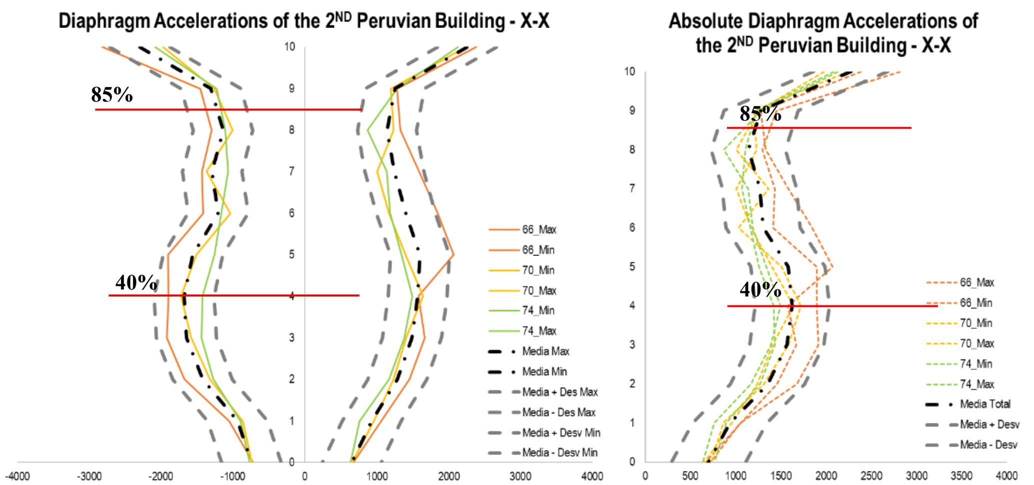


Fig. 11 – Diaphragm accelerations of the 1st Peruvian Building for the X direction and Y direction from top to bottom, respectively.



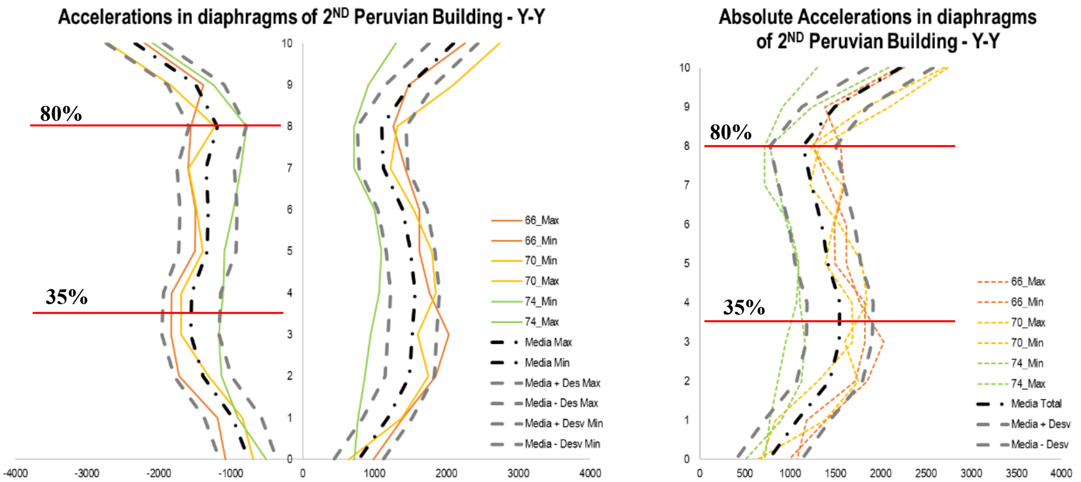
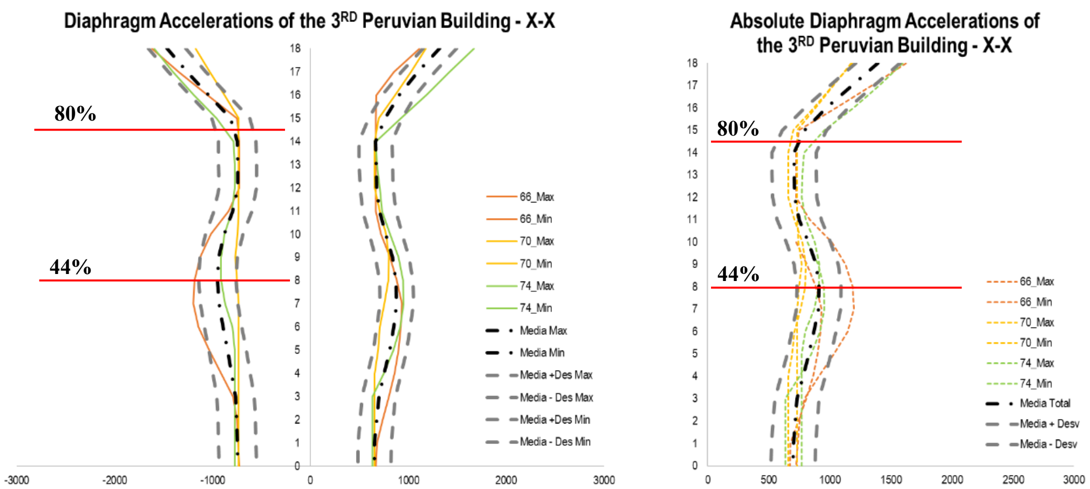


Fig. 12 – Diaphragm accelerations of the 2nd Peruvian Building for the X direction and Y direction from top to bottom, respectively.

Irregular Peruvian Buildings

For the last three buildings, maximum absolute accelerations were obtained in the top floor (approximately more than 2.0 times the maximum base acceleration) and the acceleration varies along with the building height as Fig. 13, Fig. 14 and Fig. 15 depicts. A soft variation can be identified in these figures, however, there are abrupt variations in height due to the nonlinear behaviour. See that the mean shape cannot be fitted to a polynomial curve.

For these irregular buildings the mean shape is significatively different for both axes because of the structural element distribution and the structural irregularities. The mean curves are also shown in Fig. 13, Fig. 14 and Fig. 15 as black dashed lines, likewise, a region limited by one standard deviation of the mean is enclosed by gray lines in order to show the result variation graphically.



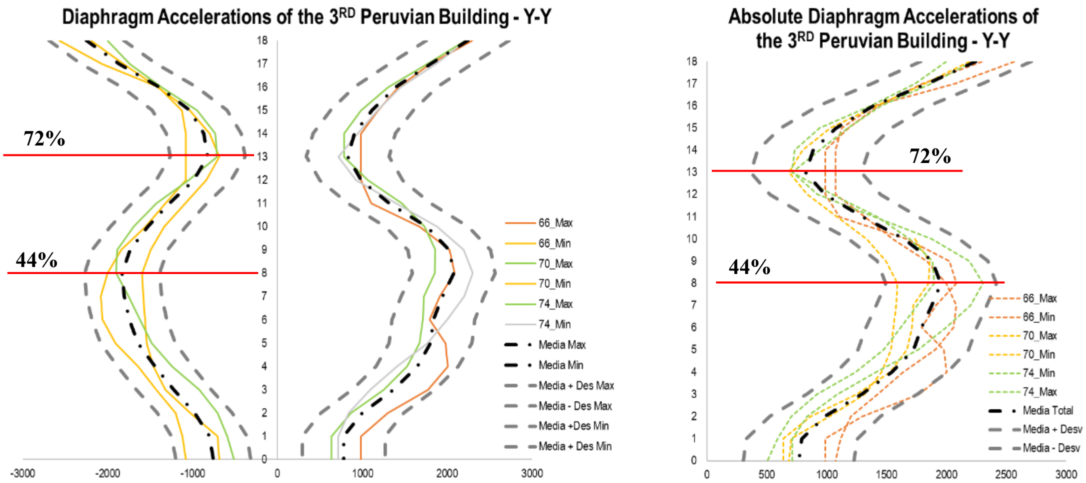


Fig. 13 – Diaphragm accelerations of the 3rd Peruvian Building for the X direction and Y direction from top to bottom, respectively.

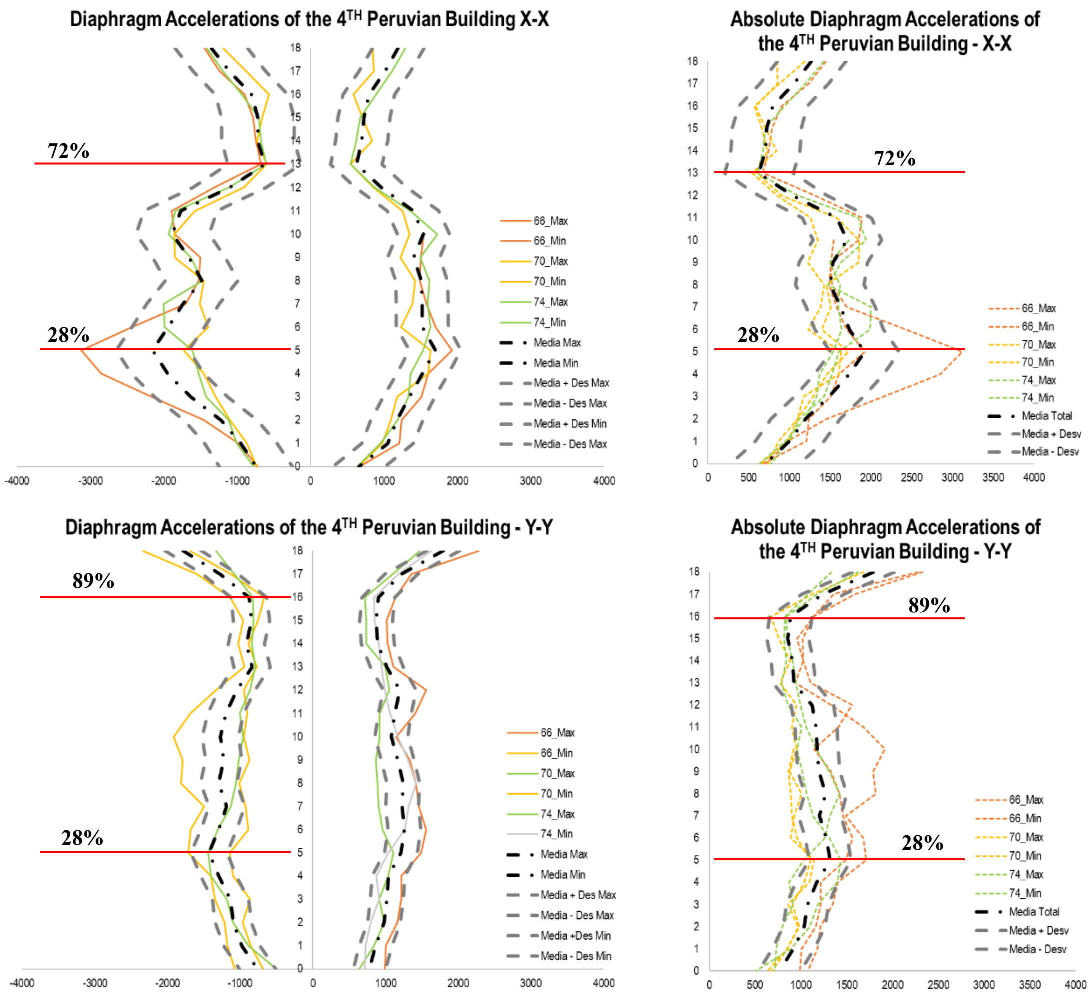


Fig. 14 – Diaphragm accelerations of the 4th Peruvian Building for the X direction and Y direction from top to bottom, respectively.

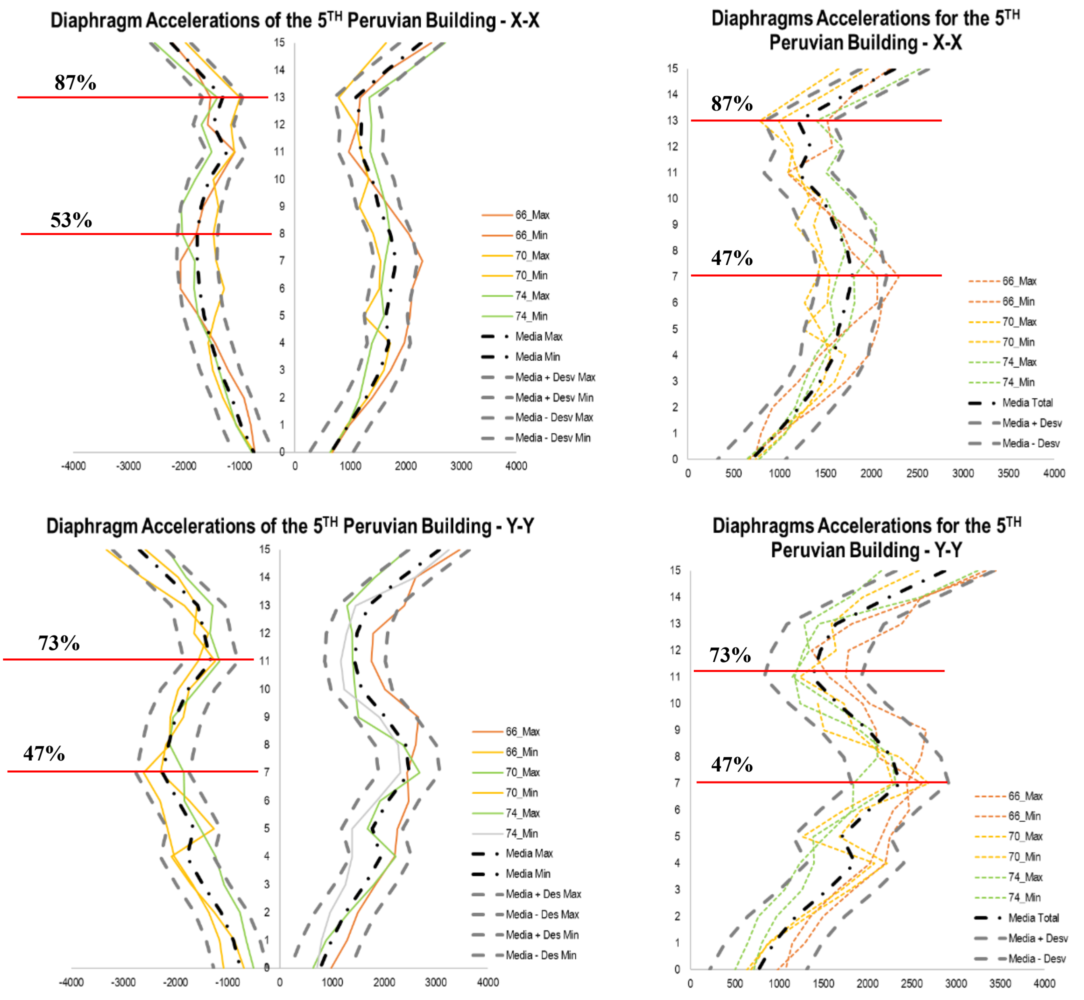


Fig. 15 – Diaphragm accelerations of the 5th Peruvian Building for the X direction and Y direction from top to bottom, respectively.

In order to make a comparison between all the results, mean diaphragm accelerations were normalized, so that, the bottom acceleration is equal to 1.0 and the height is presented in percentage. Table 2, shows the coefficients obtained for all the numerical simulations mean. With these coefficients the maximum absolute accelerations can be obtained considering that the base acceleration is obtained according to the Peruvian Standard E.030, that is to say, the absolute accelerations in each diaphragm are obtained from the product of the base shear and the coefficients previously calculated. Likewise, the diaphragm forces are obtained by multiplying the absolute accelerations by the mass of its corresponding level. Note that the coefficients and height percentages for the five buildings are different and do not form a pattern between them. The coefficients and their height distribution are related to the shape of upper modes that should be analyzed in further research.

Table 2 – Acceleration coefficients in Diaphragms obtained from the mean of numerical simulations.

1st Building		2nd Building		3rd Building		4th Building		5th Building	
%Height	Proposal	%Height	Proposal	%Height	Proposal	%Height	Proposal	%Height	Proposal
100%	3.45	100%	3.10	100%	2.50	100%	2.10	100%	3.50
80%	1.90	85%	1.50	75%	1.00	85%	1.10	85%	1.60
35%	2.15	30%	2.30	45%	2.10	30%	2.40	45%	3.00
0%	1.00	0%	1.00	0%	1.00	0%	1.00	0%	1.00

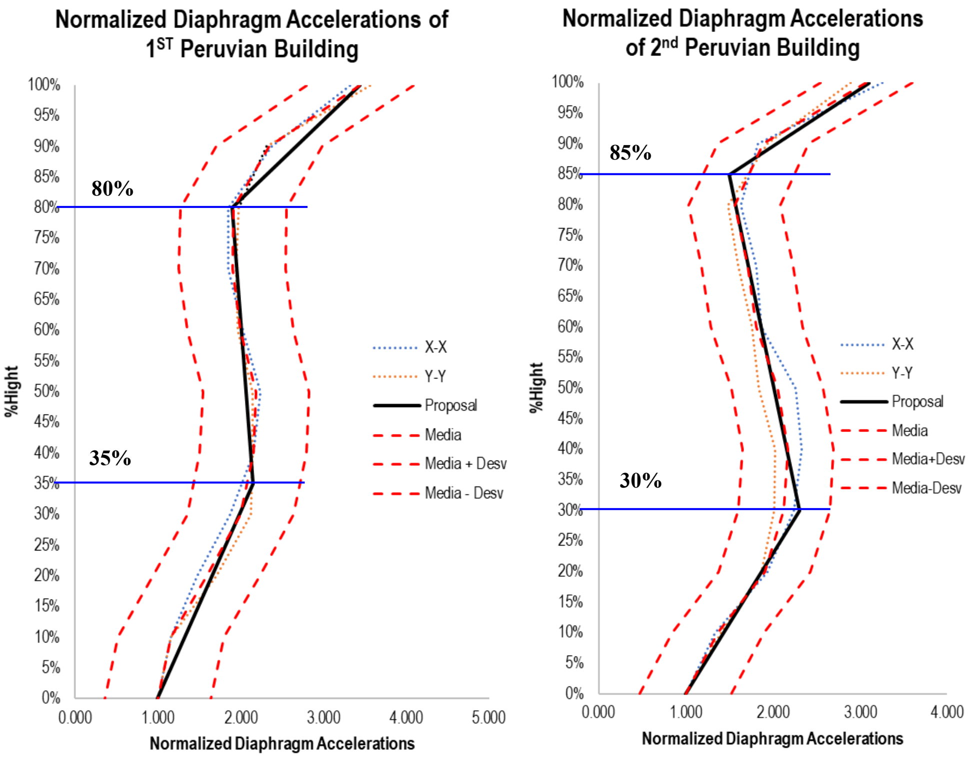


Fig. 16 – Normalized Diaphragm Accelerations for the 1st and 2nd Peruvian Building.

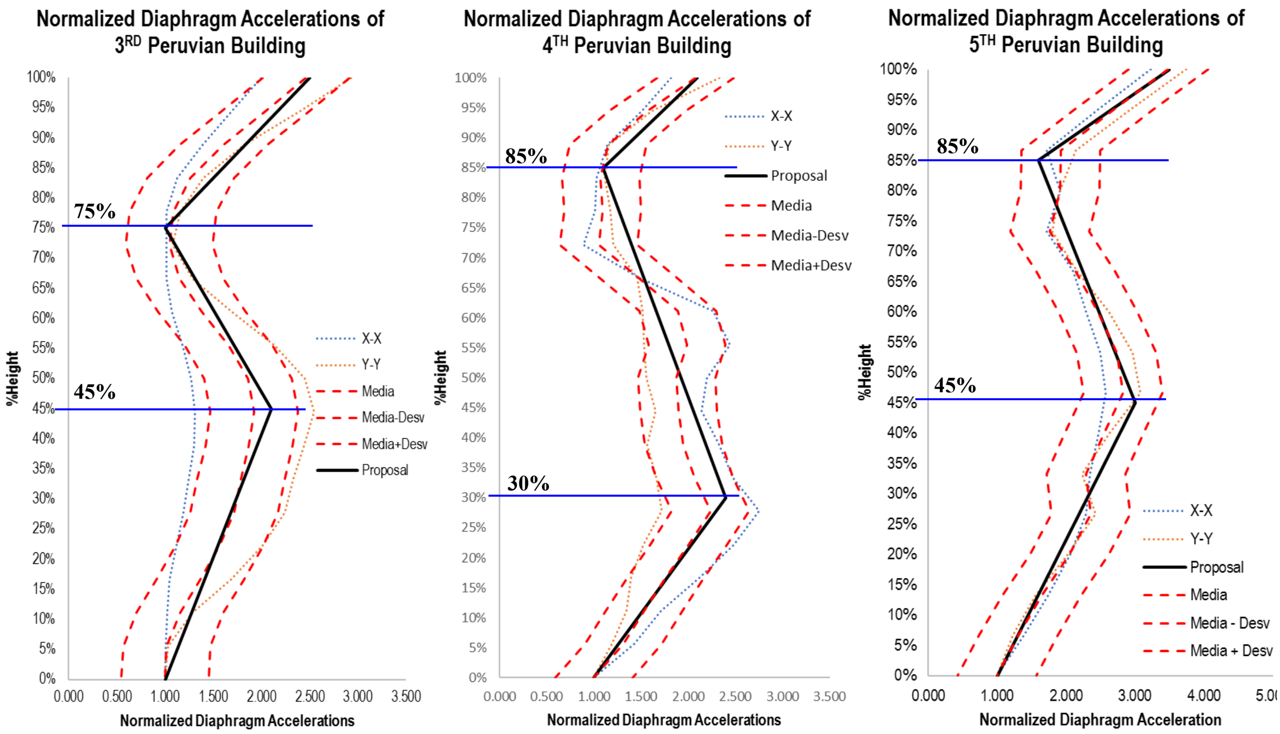


Fig. 17 – Normalized Diaphragm Accelerations for the 3rd, 4th, and 5th Peruvian Building.

6. Conclusions

Several non-linear dynamic analyses of regular and irregular Peruvian Buildings were carried out to make a comparative analysis of seismic forces in diaphragms by considering that absolute accelerations proportional to them. Results from the studies are as follows;

- In the distribution of diaphragm accelerations, two inflection points were identified roughly at 80% and 35% of the building height. Likewise, top absolute accelerations are more than two times the absolute base acceleration.
- Despite the scatter plot of absolute accelerations, the results lie within the region limited by the mean plus or minus one standard deviation, consequently a relationship can be proposed.
- Higher top accelerations were obtained in regular buildings than the irregular ones and more abrupt variations are identified in the distribution of diaphragm accelerations in irregular buildings because of the non-linear behavior of them.
- A tri-linear relationship can be set to estimate the shape of acceleration distribution thus design properly the diaphragm elements, however, coefficients to define this relation must be study in further research.

7. References

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8. Acknowledgements

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