Dynamic Amplification Factor Proposal for Seismic Resistant Design of Tall Buildings with Rigid Core Structural System

Eder Quezada, Yaneth Serrano, and Guillermo Huaco

Abstract Currently, there is an increase in the demand for tall buildings in the city of Lima. This research proposes to reduce the dynamic amplification factor through the seismic design of tall buildings based on the requirements of Peruvian code considering that they are regular in plan and height. Minimum base shear values according to the comparison of static seismic shear and dynamic shear from the spectral modal analysis were reviewed for cases of buildings larger than 120 m. The study of 28 reinforced concrete buildings was proposed, with different heights - varying from 24 to 36 floors, with different floor configurations, as well as the arrangement of the walls considering as a rigid core structural system. Additionally, the characteristics of the materials, the loads and combinations were defined. The responses of these buildings were determined by the response spectrum analysis (RSA) and then compared with those obtained by the lineal response history analysis (LRHA), for the last analysis, five Peruvian seismic records were used and scaled to 0.45 g. The seismic responses of the LRHA procedure were taken as a benchmark. The result of this study is the analysis and proposal of the *C*/*R* factor for high-rise buildings, as well as obtaining the base shear and drift verification. Minimum base shear values can be reduced for high or long-term buildings, being regular in plan and height.

Keywords High-Rise buildings · Long natural period · Minimum seismic base shear force · Rigid core

E. Quezada · Y. Serrano · G. Huaco (✉)
Peruvian University of Applied Sciences UPC, Av. Prolongación Primavera 2390, Santiago de Surco, Lima, Peru
e-mail: pccighua@upc.edu.pe

E. Quezada
e-mail: u201610055@upc.edu.pe

Y. Serrano
e-mail: u201423812@upc.edu.pe

Y. Iano et al. (eds.), *Proceedings of the 5th Brazilian Technology Symposium*, Smart Innovation, Systems and Technologies 202,
https://doi.org/10.1007/978-3-030-57566-3_24

1 Introduction

A study by the United Nations estimates that by the end of 2050, approximately 64% of developing countries and 86% of the population of developed countries will live in cities. To solve the increase in population density in urban areas, these must be expanded, or high-rise buildings built [1]. For this reason, in the last decade, Lima has experienced an increase in the verticality of its buildings. Therefore, it is necessary to use a structural system resistant to wind and earthquake forces. Based on this, several structural systems have been developed for high-rise buildings. The rigid core structural system constitutes such a solution and offers the advantage of faster construction, flexible architecture and open space availability [1–8]. To design these structures that resist earthquake loads, there are several numerical methods [2]. One of them is the response spectrum analysis (RSA) which is widely used in various seismic codes such as ASCE 7, UBC-97, FEMA-356 and ATC-40 to determine design forces and displacement demands [3]. In addition, must be taken into consideration that tall buildings are complex due to the numerous structural components and several vibration modes [4]. In the case of the Peruvian Code, this method is related to the Equivalent Lateral Force (EFL) by means of the dynamic amplification factor, which guarantees that the current base is not less than 80% of the value calculated by EFL for regular structures. To determine the shear force by means of the EFL, the Standard establishes a minimum *C*/*R* factor. The subject of this analysis is to corroborate this parameter in the case of tall buildings by comparing inelastic responses with the LRHA. In addition, few studies prove that the RSA established by the standard is adequate for high-rise buildings. The advantage of using an adequate value for this factor will avoid the design of the building with unnecessary robust elements that meet the seismic requirements, which would significantly increase the cost of such infrastructure since it would cause a lack of investment due to the cost overrun.

The methodology adopted in this work is proposed by our authorship and is described as follows:

1. The case studies are defined taking into consideration the following criteria: use of the building, dimensions, predominant material, mezzanine height, slab thickness and variation in compressive strength.
2. Selection of five seismic acceleration records according to soil type and moment magnitude range.
3. Proceed with the EFL and RSA, as established by the Seismic Resistant Design Code E.030.
4. The inelastic responses of the spectral modal dynamic analysis are compared with the linear time-history analysis to determine the adjustment of the *C*/*R* factor.
5. The results analysis is carried out and an adjusted *C*/*R* value is proposed for high-rise reinforced concrete building.

2 Methodology

2.1 Description of the Buildings

Twenty-eight tall buildings located in Lima, Peru, are considered in this study (Fig. 1). The number of floors of the cases analyzed is 24, 26, 28, 30, 32, 34 and 36 floors. Fourteen of these buildings correspond to a square plan and the other fourteen to a rectangular plan. Likewise, the structural configuration was modified considering frames and post-tensioned slabs.

Each beam and column was modeled as an elastic frame element. The slabs and the cutting walls are modeled with a thin shell elastic element and the foundation was idealized as recessed base support. For all buildings, the columns on each floor resist-less than 30% of the total lateral force; therefore, the structural system is considered as structural walls in accordance with Code E.030. The $P - \Delta$ effects are included in all the methods [5] (Table 1).

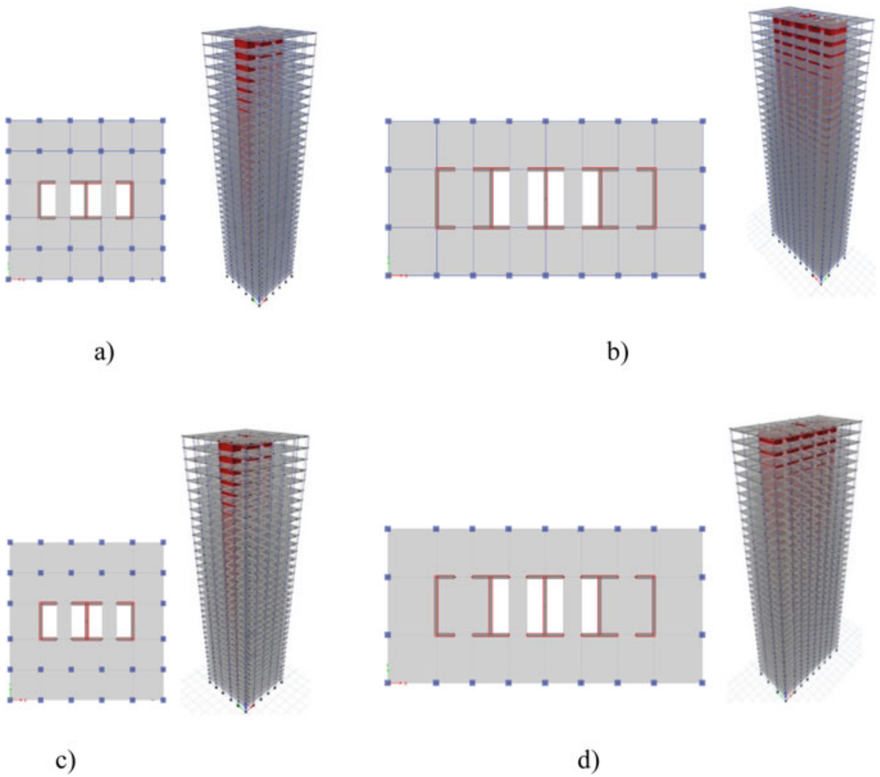

Fig. 1 Floor plans and 3D models. **a** PC-POR, **b** PR-POR, **c** PC-POS y **d** PR-POS

Table 1 Coding of the square and rectangular floor model

Number of stories	Walls and Columns		Post-tensioned slab	
	PC-POR	PR-POR	PC-POS	PR-POS
	Square	Rectangular	Square	Rectangular
24	N24-PC-POR	N24-PR-POR	N24-PC-POS	N24-PR-POS
26	N26-PC-POR	N26-PR-POR	N26-PC-POS	N26-PR-POS
28	N28-PC-POR	N28-PR-POR	N28-PC-POS	N28-PR-POS
30	N30-PC-POR	N30-PR-POR	N30-PC-POS	N30-PR-POS
32	N32-PC-POR	N32-PR-POR	N32-PC-POS	N32-PR-POS
34	N34-PC-POR	N34-PR-POR	N34-PC-POS	N34-PR-POS
36	N36-PC-POR	N36-PR-POR	N36-PC-POS	N36-PR-POS

2.2 Selected Seismic Records

In this study, a set of five seismic records was selected and the information was obtained from the Japanese Peruvian Center for Seismic Research and Disaster Mitigation (CISMID) [7]. The selection of these registers took into consideration the type of soil where the building is to be cemented (Very rigid soil) and with magnitude in the range of 6–8.5-moment magnitude. In addition, these were scaled to 0.45 g cm/s^2 (Fig. 2).

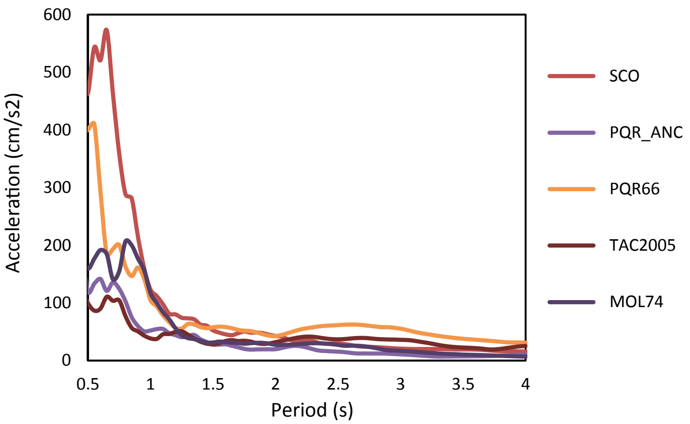

Fig. 2 The response spectrum of selected earthquakes with a damping of 5%

2.3 *Methods of Analysis for Earthquake Resistant Design*

2.3.1 Equivalent Lateral Force Procedure (ELF)

The ELF procedure in Code E.030 is adopted in this study [6]. This method represents the seismic solicitations as a set of lateral forces that act in the center of mass of each level of the building. It consists of determining five seismic parameters that are: zone factor (*Z*), soil factor (*S*), use factor (*U*), seismic amplification factor (*C*), seismic force reduction coefficient (*R*). The determination of the shear force at the base of the structure for each direction considered is calculated as follows:

$$V = \frac{ZUCS}{R} \cdot P; \frac{C}{R} \geq 0.11 \quad (1)$$

This methodology cannot be applied to structures of reinforced concrete bearing walls for buildings with a height greater than 30 m. However, it is necessary to carry out this analysis in the design of reinforced concrete elements by what establishes the norm as a minimum base shear force.

2.3.2 Response Spectrum Analysis (RSA)

The RSA method in Code E.030 is adopted in this study [6], where the elastic response is combined for several vibration modes to obtain the total elastic response, using the complete quadratic combination (CQC), which is then reduced by a force reduction factor (*R*) to obtain the design forces of the structure.

3 Results

3.1 *Comparison of Design Demands Between RSA and LRHA*

The following graphs represent the base shear through different types of analysis in both directions. The first bar represents the RSA analysis with the *C*/*R* factor calculated, while the second bar depicts the base shear obtained with the RSA analysis with the minimum *C*/*R* factor proposed by the Peruvian Code. Addition-ally, the other bars represent the base shear calculated from LRHA analysis with the seismic records mentioned above (Figs. 3, 4, 5, 6, 7, 8, 9 and 10).

The shear forces calculated from the LRHA are significantly lower than those calculated from RSA established by the Peruvian Standard of Seismic-Resistant Design E.030, only a few exceptions for the seismic record of Surco1974 for the N34PC_POR model. Therefore, it can be deduced that the *C*/*R* value is lower than what is established in the regulations. The results of the LRHA were reduced by a factor *R*. There are greater requests in terms of cut in square and rectangular plants of 36 levels.

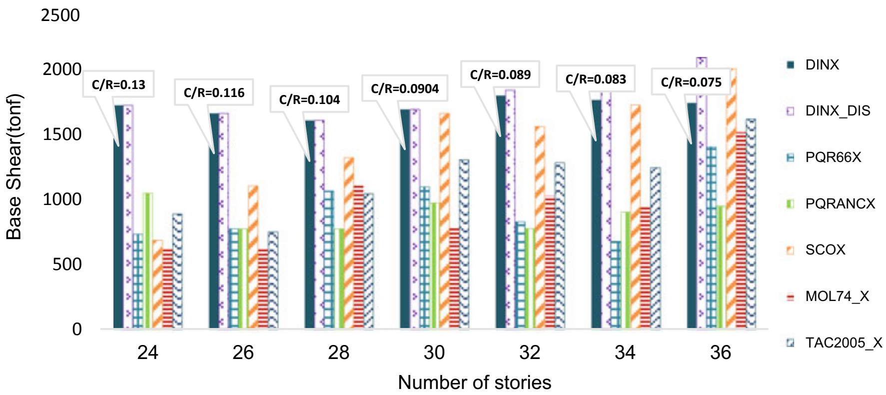

Fig. 3 Base Shear for PC-POR in the *X*-direction

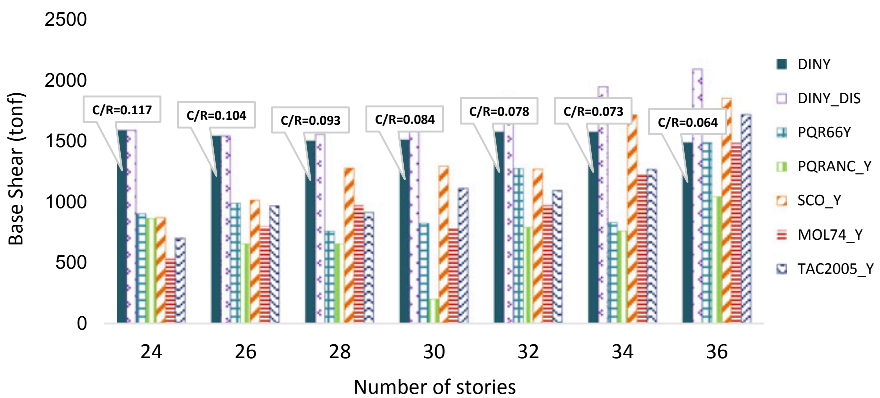

Fig. 4 Base Shear for PC-POR in the *Y*-direction

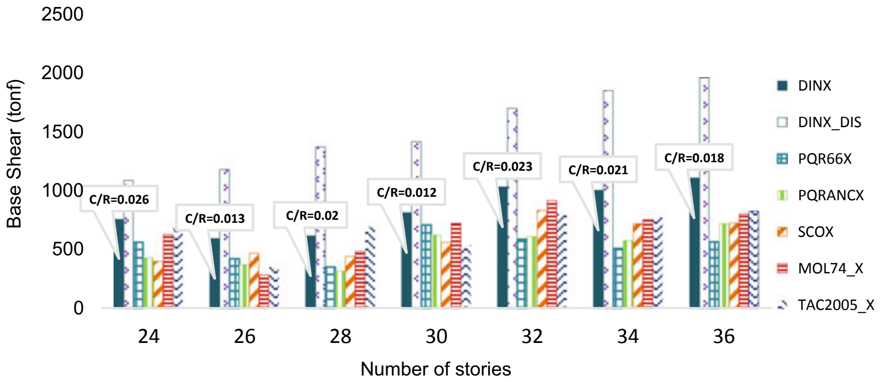

Fig. 5 Base Shear for PC-POS in the *X*-direction

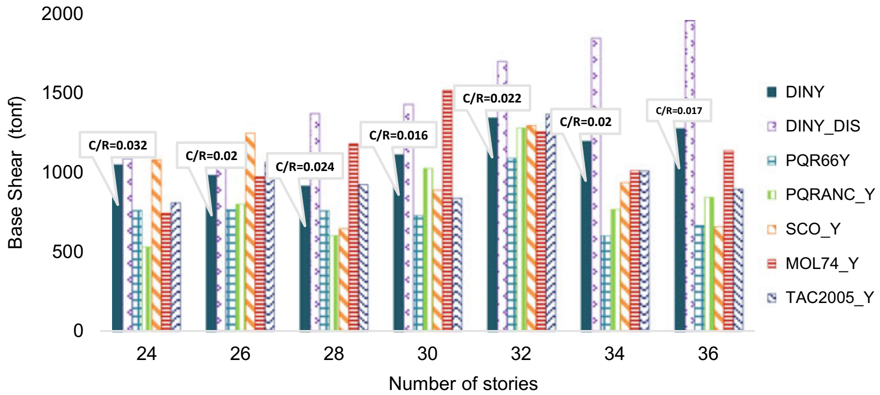

Fig. 6 Base Shear for PC-POS in the *Y*-direction

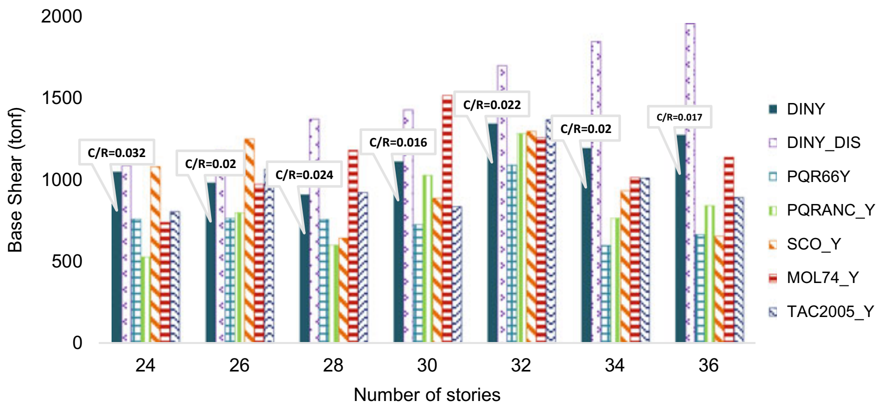

Fig. 7 Base Shear for PR-POR in the *X*-direction

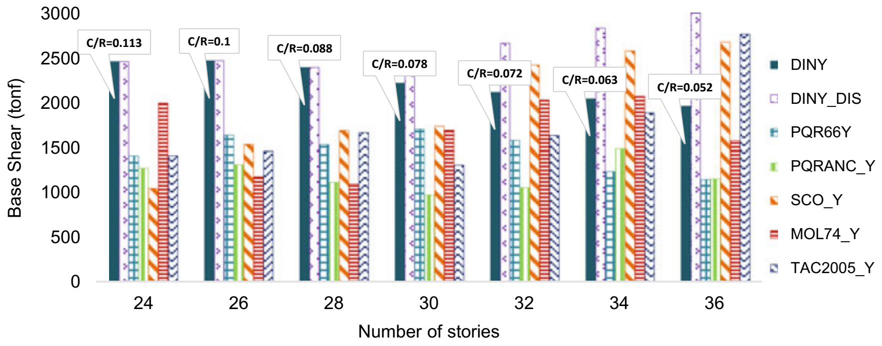

Fig. 8 Base Shear for PR-POR in the *Y*-direction

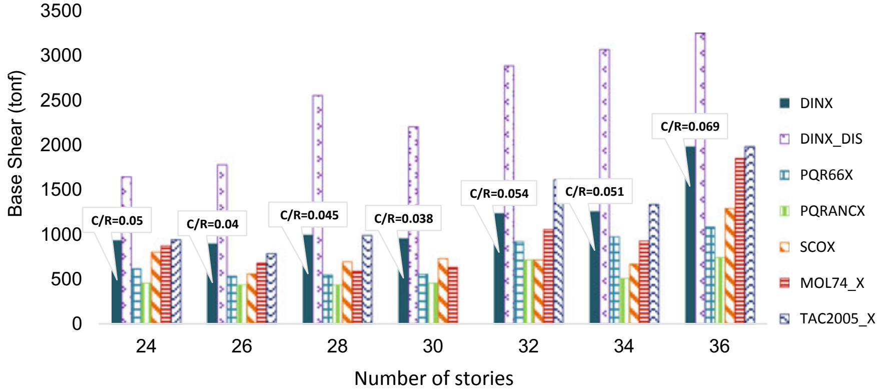

Fig. 9 Base Shear for PR-POS in the *X*-direction

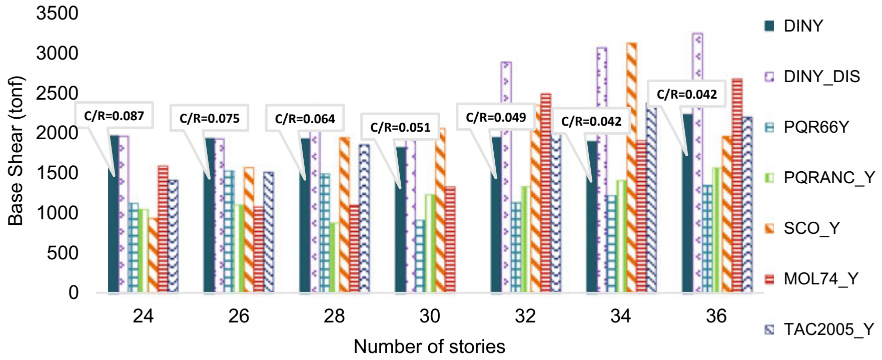

Fig. 10 Base Shear for PR-POS in the *Y*-direction

The general procedure to determine the value of *C*/*R* for high-rise buildings consists of computing ratios that are based on the base shear obtained by the RSA and the LRHA. Then the ratios are multiplied by the *C*/*R* values obtained from the LRHA. Finally, the most critical values were chosen as the final value (Tables 2 and 3).

Table 2 Summary of proposed *C*/*R* values in the *X*-direction

				C/*R* proposed				
	Level	Tx	*C*/*R* calc.	PQR 66	PQR70	SCO74	MOL74	TACNA
PC-POR	24	1.284	0.13	0.055	0.079	0.052	0.047	0.067
	26	1.441	0.116	0.054	0.054	0.077	0.044	0.052
	28	1.602	0.104	0.069	0.050	0.085	0.072	0.067
	30	1.779	0.094	0.061	0.054	0.092	0.044	0.072
	32	1.873	0.089	0.041	0.039	0.077	0.051	0.063
	34	2.01	0.083	0.032	0.043	0.081	0.045	0.058
	36	2.23	0.075	0.060	0.041	0.086	0.065	0.070
PC-POS	24	2.666	0.059	0.044	0.033	0.031	0.049	0.054
	26	3.848	0.028	0.020	0.017	0.022	0.013	0.017
	28	3.074	0.044	0.025	0.023	0.031	0.034	0.049
	30	3.91	0.027	0.024	0.021	0.019	0.024	0.018
	32	2.863	0.051	0.029	0.030	0.041	0.045	0.040
	34	2.96	0.048	0.024	0.027	0.034	0.036	0.037
	36	3.229	0.04	0.020	0.026	0.026	0.029	0.030
PR-POR	24	1.111	0.15	0.059	0.097	0.069	0.100	0.097
	26	1.229	0.136	0.055	0.064	0.054	0.063	0.071
	28	1.353	0.123	0.060	0.072	0.085	0.047	0.052
	30	1.542	0.108	0.058	0.042	0.066	0.053	0.052
	32	1.557	0.107	0.070	0.053	0.079	0.064	0.063
	34	1.696	0.098	0.066	0.040	0.097	0.069	0.072
	36	1.835	0.091	0.045	0.045	0.084	0.052	0.073
PR-POS	24	2.901	0.05	0.033	0.025	0.043	0.047	0.050
	26	3.227	0.04	0.024	0.020	0.025	0.030	0.035
	28	3.045	0.045	0.025	0.020	0.032	0.027	0.045
	30	3.317	0.038	0.022	0.018	0.029	0.025	0.038
	32	2.789	0.054	0.040	0.031	0.031	0.046	0.071
	34	2.853	0.051	0.040	0.021	0.027	0.038	0.054
	36	2.401	0.069	0.038	0.026	0.045	0.064	0.069

Table 3 Summary of *C*/*R* proposed values in the *Y*-direction

				C/*R* proposed				
	Level	Ty	*C*/*R* calc.	PQR 66	PQR70	SCO74	MOL74	TACNA
PC-POR	24	1.426	0.117	0.066	0.064	0.064	0.039	0.052
	26	1.605	0.104	0.067	0.044	0.068	0.054	0.065
	28	1.786	0.093	0.047	0.041	0.079	0.060	0.057
	30	1.975	0.084	0.046	0.047	0.072	0.044	0.062
	32	2.152	0.078	0.063	0.039	0.063	0.048	0.054
	34	2.298	0.073	0.038	0.035	0.080	0.057	0.059
	36	2.55	0.064	0.064	0.045	0.080	0.064	0.074
PC-POS	24	2.32	0.072	0.052	0.036	0.074	0.051	0.056
	26	3.04	0.045	0.035	0.037	0.057	0.045	0.049
	28	2.78	0.054	0.045	0.036	0.038	0.070	0.055
	30	3.446	0.035	0.023	0.032	0.028	0.048	0.026
	32	2.904	0.049	0.040	0.047	0.047	0.046	0.050
	34	3.04	0.045	0.023	0.029	0.035	0.038	0.038
	36	3.349	0.037	0.019	0.025	0.019	0.033	0.026
PR-POR	24	1.472	0.113	0.065	0.058	0.048	0.092	0.065
	26	1.672	0.1	0.066	0.053	0.062	0.048	0.059
	28	1.886	0.088	0.056	0.041	0.062	0.040	0.061
	30	2.149	0.078	0.060	0.034	0.061	0.060	0.046
	32	2.321	0.072	0.054	0.036	0.082	0.069	0.056
	34	2.58	0.063	0.038	0.046	0.080	0.064	0.058
	36	2.843	0.052	0.030	0.031	0.071	0.042	0.073
PR-POS	24	1.928	0.087	0.050	0.046	0.041	0.071	0.063
	26	2.235	0.075	0.059	0.043	0.061	0.042	0.059
	28	2.549	0.064	0.049	0.029	0.065	0.036	0.062
	30	2.872	0.051	0.025	0.035	0.058	0.037	0.042
	32	2.906	0.049	0.029	0.034	0.059	0.063	0.051
	34	3.162	0.042	0.027	0.031	0.070	0.042	0.053
	36	3.146	0.042	0.025	0.029	0.037	0.050	0.041

4 Discussions

This work incentive the design of buildings that meet the seismic requirements and is economically feasible, besides that it was resolved the lack of information regarding high-rise reinforced concrete buildings in Peru and investigates the advantages of regular seismic buildings as seen in other international buildings such as the case of Burj Khalifa.

The range of periods found for the PC-POR and PR-POR buildings is between 1.5 and 3 s, while for the PC-POS and PR-POS structures their range corresponds to 2.5–4 s, being the largest period, the cross-section that is slenderer.

5 Conclusions

The value of *C*/*R* is analyzed in the case of tall reinforced concrete buildings by comparing the design shears indicated by Peruvian seismic regulations with the base shear obtained from an LRHA, which have been scaled to 0.45 g.

It was found lower drifts of the LRHA smaller than what is indicated in Code E.030, except for specific cases, but all are less than 0.7%, which establishes said norm. The dynamic amplification factor is sensitive to the *C*/*R* value. It was noticed that for PC-POR and PR-POR buildings, considering the minimum *C*/*R* equal to 0.11, the shear does not need to be amplified for buildings smaller than 30 floors, however, for larger buildings the factor of amplification would be in the order of 150%. On the other hand, for PC-POS buildings, it is not necessary to amplify the shear, and for PR-POS it is amplified from the 32-story buildings, in the order of 250%.

The main finding of this paper proposes a minimum value of *C*/*R* less than 0.11 for each of the 4 studied cases of the high-rise building. It was obtained due to the regularity in the plan and height of the building and the use of a rigid core structural system. As for PC-POR buildings, it is established that *C*/*R* values are much lower than 0.08 for buildings with up to 32 levels, for buildings with a higher number of levels this value is close to 0.08; something similar happens for structures type PR-POR. In addition, for PC-POS and PR-POS buildings, the value of *C*/*R* is less than 0.08 at all levels. Two *C*/*R* values differentiated by the structural system are proposed, *C*/*R* equal to 0.075 for PC-POS and PR-POS and for 0.10 for PC-POR and PR-POR.

There is a pressing need to extend the research to study the implications of the wind force due to the predominant effect for high-rise buildings such as this one because of its high natural period. It is suggested to study it. Furthermore, the value of R must be improved or studied, being able to be less than 6, for this, it is suggested to perform a nonlinear response history analysis (NLRHA).

References

1. Rahman, A., Zaman, Q., Irshad, M.: Evaluation of Simplified Analysis Procedures for a High-Rise Reinforced concrete core wall structure. Adv. Civil Eng. **16**, 599–614 (2019)
2. Khy, K., Chintanapakdee, C., Wijeyewickrema, A.: Modified response spectrum analysis to compute shear force in tall RC shear wall buildings. Eng. Struct. **180**, 295–309 (2019)

3. Najam, F, Warnitchai, P.: A modified response spectrum analysis procedure to determine nonlinear seismic demands of high-rise buildings with shear walls. Struct. Des. Tall Special Build. **27** (2017)
4. Mehmood, T., Warnitchai, P., Suwansaya, P.: Seismic evaluation of tall buildings using a simplified but accurate analysis procedure. J. Earthq. Eng. **22**(3), 356–381 (2017)
5. Liu, Y., Kuang, J.: Spectrum-based pushover analysis for estimating seismic demand of tall buildings. Bull. Earthq. Eng. **15**, 4193–4214 (2017)
6. Peru Seismic Code E.030.: Seismic Design Requirements for Buildings, SENCICO, Peru (2018)
7. Accelerometers Network Database, Center for Earthquake Engineering Research and Disaster Mitigation, CISMID, Lima Peru (2019)
8. Ali, M., Moon, K.: Advances in structural systems for tall buildings: emerging developments for contemporary urban giants. Buildings **8**, 104 (2018)