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Comparative study of costs for reinforced concrete portico buildings designed with different degrees of seismic performance

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Comparative study of costs for reinforced concrete portico buildings designed with different degrees of seismic performance

J R Cáceres[1], J F Márquez[1], and J P Rojas[1]
[1] Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: joserafaelcr@ufps.edu.co

Abstract. The Colombian regulation of earthquake resistant construction NSR-10 establishes that the seismic-resistant capacity of a building must be classified according to three degrees of energy dissipation: Special energy dissipation, moderate energy dissipation and minimum energy dissipation. The dimensioning and detailing requirements for structural elements that are demanded according to each grade depend on the need to withstand earthquakes in the inelastic range according to the seismic hazard zone in which the structure is located. This work presents an analysis of the incidence of the requirements of each degree of energy dissipation on the costs of multi-storey building structures. For this, the structural analysis and design of four building configurations (2, 3, 4 and 5 floors) for each minimum energy dissipation, moderate energy dissipation, and special energy dissipation grade has been carried out and the quantities of work with their respective total cost have been determined. As a general conclusion, it can be stated that the cost of building a structure that has special energy dissipation capacity for a given building can be twice that of a structure that has minimum energy dissipation capacity for the same building. On the other hand, it was observed that in order to guarantee a rigidity comparable to that of the other models analyzed, the system of reinforced concrete portal resistant to moments for DES level requires large column dimensions in the case of buildings of four or more floors, which suggests that other types of more efficient elements should be used in the vertical seismic resistance system.

1. Introduction

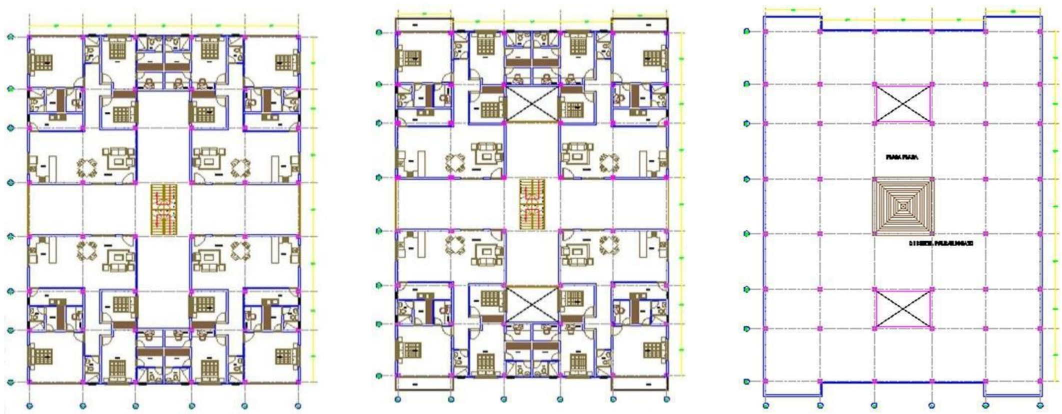
The Colombian Regulation of Earthquake Resistant Construction, NSR-10, recognizes three degrees of energy dissipation: special energy dissipation (DES), moderate energy dissipation (DMO) and minimum energy dissipation (DMI). Each degree of energy dissipation can be guaranteed by meeting minimum dimensional requirements, detailed reinforcement and structure configuration [1,2].

In Colombia, several investigations have been carried out to study the effect of the earthquake-resistant requirements of the regulations in force in the country on relevant aspects for builders and designers. For example, [3] studied the behavior that structures would have when varying the degree of energy dissipation in the design of seismic-resistant structures following the previous regulation [1-4] evaluated seismic vulnerability in the design of structures by performance according to the same standard [4] and [5] investigated the effect of varying the degree of energy dissipation on the amounts of work for buildings constructed using reinforced concrete walls [5].

The construction costs of building structures usually consume a significant part of the investment, so it is essential to sustain research on them involving the effects of varying structure properties, construction techniques and environmental conditions. In Indonesia, [6] examined the performance of constructions of large buildings (hotels, hospitals, offices, etc.), showing that costs tend to vary with sizes at a constant rate, according to capacity cost factors close to the unit [6]. The American Association of cost engineers presents a cost estimation classification system, for which typical estimation methods are stochastics or judgments with independent variables, which are generally more than a direct measure of the units of estimated elements [7]. This paper focuses on the observation of the effects of variation in the properties of the structure by presenting an analysis of the variation in the costs of typical building structures when they are designed to guarantee different degrees of energy dissipation according to the definition of the current regulation [1].

2. Methodology

A typical floor plan was used with a functional architectural design for housing that was repeated in height to conform four different buildings each with a total elevation of 2, 3, 4 and 5 floors. Each building was structured using a moment resistant three-dimensional gantry system whose elements were designed for the three degrees of energy dissipation described by [1], DES, DMO and DMI. Therefore, the sample of the experiment consisted of twelve buildings. The cost models must be valid and precise, which implies the testing and evaluation of the developed models [8-10]. The chosen architectural design has a floor area of 741.57 $m^2$and a floor free height of 2.40 m. Column center distances ranged from 3.50 m to 5.00 m and were fixed from the beginning for all the buildings analyzed, see Figure 1.



(a) (b) (c)

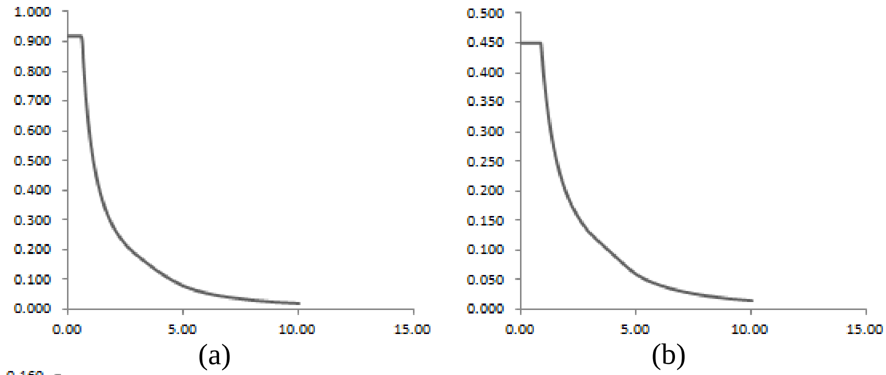
Figure 1. Typical architectural (a) first floor, (b) mezzanine floor (c) roof.

The typical mezzanine slab was assembled by arranging ribs in two directions each 10 cm wide and a total height of 40 cm (including 5 cm thick tile). The typical lightening vacuum was configured with 35 cm height and 60 cm width. The structural analysis of each model was done with the help of SAP2000® software [11]. The typical floor load analysis can be seen in Table 1.

Table 1. Gravitational loads considered (Living and Dead).

Description		Load (kN/m^2)
Dead Load	Upper Tile	1.20
	Nerve	1.20
	Masonry	3.00
	Refined	1.60
	“Enchape”	0.15
	Ceiling	0.20
	Total	7.35
Live load balcony		5.00
Live load rooms		1.80

The soil profile used was the one defined in NSR-10 as type C, which is considered to describe a wide range of sites where buildings are located in urban areas of Colombia. The bearing capacity of the soil was set at $120\,\mathrm{kN/m^2}$. According to the seismic hazard zone and site effects, design spectra were plotted for each performance level presented in Figure 2.



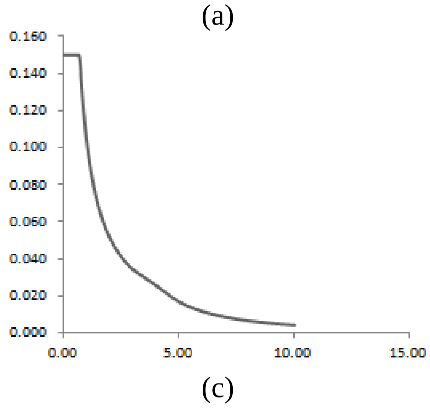


Figure 2. Design spectra by performance level (a) DES, (b) DMO and (c) DMI.

Each moment resistant reinforced concrete gantry structural system was modeled using reinforced concrete parameters. The basic energy dissipation coefficient, R0, for each degree of energy dissipation was assigned as stated in NSR-10, i.e. $R_0 = 7.0$ for DES; $R_0 = 5.0$ for DMO and $R_0 = 2.5$ for DMI.

For the evaluation of seismic effects, the dynamic method was used, and its results were adjusted to the minimum requirements associated with the equivalent horizontal force (EHF) method as established in NSR-10. Therefore, the design seismic forces were obtained by calculating the extreme values in each member generated by each design spectrum by exciting the structure in the two main directions (U1 and U2). To find the results as maximum design values, the full quadratic combination of modes (CQC) method was used, while the square root of the sum of squares (SRSS) method was applied to calculate the resulting values by orthogonal effects.

Once the seismic forces adjusted according to the above were obtained, the final configuration for the design of each structure was defined in an iterative process with the criterion of obtaining a floor drift that oscillated around 1% $(1 \pm 0.1\%)$ of the height of the most flexible floor complying with NSR-10. This could be achieved in the conditions for DES and DMO. However, in the DMI condition the dimensional requirements of columns and beams to support gravitational load controlled the chosen configuration.

Once the drifts presented had been obtained, the complete design of each of the elements of the structure was drawn up, considering all the reinforcement detailing requirements established in NSR-10 for each degree of energy dissipation. The design used a concrete strength of $f'_c = 21$ MPa and steel $F_y = 420$ MPa. The maximum drifts obtained and the floor on which they occurred are shown in Table 2.

Table 2. Maximum floor drifts.

	N° of levels	Floor with greater drift	Section floor column with greater drift	Height between floors with greater drift (m)	Drift value (m)
DES	5	Fifth	95 cm x 95 cm	2.80	0.0275
	4	Fourth	70 cm x 70 cm	2.80	0.0275
	3	Third	45 cm x 45 cm	2.80	0.0275
	2	Cover	35 cm x 35 cm	2.80	0.0220
DMO	5	Third	50 cm x 50 cm	2.80	0.0260
	4	Third	40 cm x 40 cm	2.80	0.0263
	3	Third	35 cm x 35 cm	2.80	0.0210
	2	Second	30 cm x 30 cm	2.60	0.0144
DMI	5	Third	35 cm x 35 cm	2.80	0.0154
	4	Fourth	30 cm x 30 cm	2.80	0.0180
	3	Third	30 cm x 30 cm	2.80	0.0098
	2	Second	25 cm x 25 cm	2.60	0.0078

With the design plans obtained for the twelve buildings analyzed, the quantities of work and the construction costs of each one of the structures were calculated.

Table 3 presents an example of the items considered and their costs in Colombian pesos (COP) (Prices taken from “Construprecios”). The values obtained in each case were also converted to U.S. dollars (USD).

Table 3. Budget for 5-storey DES type building structure in Colombian pesos (COP).

Element	Description	Unit	Quantity	Unitary value	Partial value (millions)	Group value (millions)
Foundations	Concrete shoes	m^3	331.931	$ 553 983.78	$ 183.88	$ 499.84
	Reinforcement of shoes	kg	11068	$ 7 316.84	$ 80.98	
	Concrete beam foundation	m^3	104.433	$ 612 956.43	$ 64.01	
	Reinforcement of foundation beam	kg	23403	$ 7 305.18	$ 170.96	
Columns	Concrete columns	m^3	545.832	$ 762 736.76	$ 416.33	$ 1 110.20
	Reinforcement	kg	95012	$ 7 302.98	$ 693.87	
Mezzanine beams	Concrete 21 MPa	m^3	163.92	$ 846 880.12	$ 138.82	$ 878.62
	Reinforcement	kg	36553	$ 7 294.50	$ 266.64	
	Overall value	m^2	2562.744	$ 153 099.23	$ 392.35	$ 392.35
Mezzanine slab	Overall value	m^2	640.686	$ 126 122.41	$ 80.80	$ 80.80
		Total value structure			$ 2 488.66	

3. Results

After determining the total costs of each of the structures designed, the cost per square meter (m^2) used in this study as a comparison parameter was calculated. This parameter is valid for residential buildings that are built with a structural system of a moment resistant reinforced concrete portal with different degrees of energy dissipation depending on the height of the structure.

In order to determine the real costs of materials, labor, and equipment, the commercial prices in force in Colombia for the first semester of 2019 were used. The conversion to USD was made considering that each USD is equivalent to COP $3151 prices should be adjusted for location and time to ensure that observations are based on the same reference point, a process called data standardization, involving a cost index (a dimensionless number that relates the cost of an item at a specific time to the corresponding cost in a specified time) [12].

Table 4 and Figures 3 present a summary of the results of the cost analysis. In it, the cost overrun is evaluated as the difference between the cost of the DES or DMO type structure and the cost of the DMI

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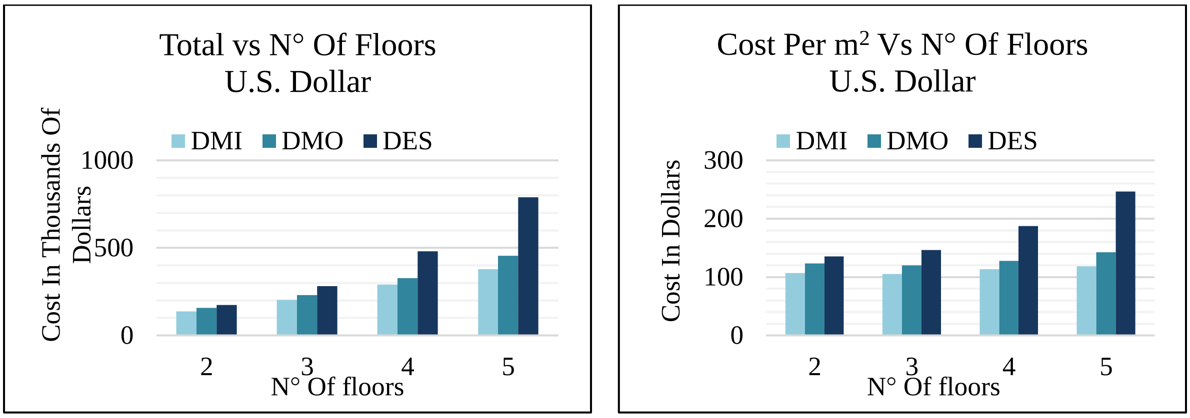
type structure. It is observed the important influence that the seismic-resistant requirements have on the cost of the structure. The cost multiplier effect of the total height of the building is also evident. Thus, for example, while for two-stories buildings the cost increase is in the order of a quarter for DES-type structures with respect to DMI-type structures, the cost increase is about double for five-stories buildings.

Table 4. Comparison of costs of structures according to the degree of performance and height.

Number of floors and degree of dissipation		Total area (m^2)	Total Value		Value per m^2		Cost overrun over DMI	Cost overrun with respect to DMO
			Million COP	Thousand USD	Thousand COP	USD		
	DES	3708	$ 2 488.66	$ 789.80	$ 776.87	$ 246.55	108%	73%
5	DMO	3708	$ 1 435.98	$ 455.72	$ 448.26	$ 142.26	20%	0%
	DMI	3708	$ 1 193.63	$ 378.81	$ 372.61	$ 118.25	0%	N/A
	DES	2966	$ 1 514.21	$ 480.55	$ 590.86	$ 187.51	65%	47%
4	DMO	2966	$ 1 032.83	$ 327.78	$ 403.02	$ 127.90	13%	0%
	DMI	2966	$ 916.09	$ 290.73	$ 357.46	$ 113.44	0%	N/A
	DES	2225	$ 887.45	$ 281.64	$ 461.72	$ 146.53	39%	22%
3	DMO	2225	$ 728.62	$ 231.23	$ 379.08	$ 120.31	14%	0%
	DMI	2225	$ 638.42	$ 202.61	$ 332.16	$ 105.41	0%	N/A
	DES	1483	$ 547.16	$ 173.65	$ 427.02	$ 135.52	27%	10%
2	DMO	1483	$ 497.57	$ 157.91	$ 388.31	$ 123.23	15%	0%
	DMI	1483	$ 431.77	$ 137.03	$ 336.96	$ 106.94	0%	N/A

On the other hand, the cost overrun of a DES-type structure over a DMO-type structure can range from 10% to 73% for buildings between 2 and 5 stories respectively indicating the same trend of cost increase when the height increases.



(a) (b)

Figure 3. Costs in USD according to performance level per number of floors: (a) Total cost, (b) Cost per m^2.

When observing Figure 4 it is evident that the incidence of the variation in height in the cost per m^2 is small for structures type DMO and DMI (the additional cost for 5 floors with respect to 2 floors is of the order of 15%), that is to say that it can be expected that the influence of the seismic-resistant requirements is not very important in these two cases. In contrast, DES structures present an important growth in the cost per m^2 produced by the demanding seismic-resistant requirements (the additional cost for 5 floors with respect to 2 floors is of the order of 82%). It is possible that this effect is related in an important way with the restriction of this study of using only columns in the structural system and its low contribution of rigidity for structures of several floors.

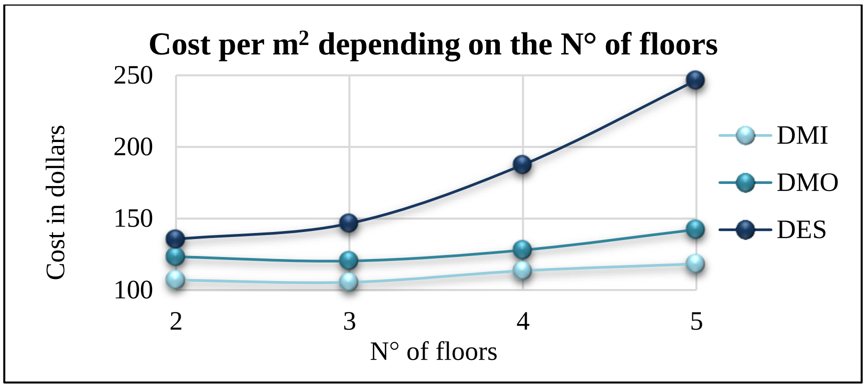


Figure 4. Trend of costs in m^2 in USD according to performance level by number of floors.

The curves shown in Figure 4 were adjusted by polynomial regression using the least squares method [12]. The best fit was obtained for a second-degree polynomial curve and its equation is shown for each case in Table 5.

Table 5. Equations of the regression curves for each degree of energy dissipation ($2 \leq x \leq 5$).

Degree of performance	Equation of the trend curve
DMI	$y = 1.583\, x^2 - 6.881x + 113.73$
DMO	$y = 4.322x^2 - 23.784x + 153.33$
DES	$y = 12.005x^2 - 46.628x + 180.16$

In the equations of Table 5 the decimal point is indicated, and the variables are given by: x = height in number of floors (2, 3, 4, 5), y = cost in USD per square meter.

4. Conclusions

The additional cost imposed by the requirements of seismic resistance in buildings of 2 and 5 floors is of the order of 27% and 108% respectively for structures type DES with respect to structures type DMI. This indicates that the structure of a 5-storey DES-type building can cost slightly more than double that of a DMI-type building of the same height. Also, the cost of 2- and 5-story DES structures can range from 110% to 173% of the cost of DMO structures for the same heights. In general, it is evident that there is a tendency to increase cost when the height increases.

The variation in height has little influence on the cost per m^2 for structures such as DMO and DMI (the additional cost for 5 floors compared to 2 floors is about 15%). In contrast, the same variation in height in structures type DES generates an important increase in the cost per m^2 (the additional cost for 5 floors with respect to 2 floors is of the order of 82%). Therefore, it is evident that the influence of seismic-resistant requirements on costs is much less important for DMI or DMO type buildings than for DES type buildings.

This work has proposed equations that relate the cost per m^2 with the total height of the structures according to their seismic-resistant quality (DMI, DMO, DES). The best fit has been achieved by using second-degree polynomials.

For DMI or DMO structures it can be stated that the cost per m^2 is more or less uniform for two to five story buildings that have the same degree of energy dissipation. However, in the case of DES-type structures this is only true for two or three-stories buildings. This seems to indicate that the stiffness provided by the columns is sufficient to meet the drift requirements in DMI or DMO structures for buildings up to five stories and only for low buildings (up to three stories) in DES structures.

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