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Estimation of Additional Costs by Seismic Safety in Shallow Foundations Projects

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Abstract: Additional costs for seismic safety in shallow foundation projects for five reinforced concrete buildings with different dimensions in plan and prop, in the city of Santiago de Cuba, an area of greatest seismic danger in Cuba are evaluated. Costs of foundation plates for seismic, wind load and gravity loads are compared separately. Physical mechanical properties were obtained from testing soil samples by SPT test at the construction area. Requirements for designing foundation plates result from the structural modeling using SAP 2000 NL version 14 for combination load according to current Cuban regulations. The book Excel DISCAR 3.0 was used for designing the geotechnical and structural foundation. Budgets were calculated by using the PRESWIN program, showing increases costs for seismic safety of foundation plates between 34 to 66% in relation to similar costs obtained by wind loads or gravitational loads, significantly increasing the dimensions of foundation's plates, concrete and excavation volumes as well as total reinforcing steel weight for seismic loads.

Key words: shallow foundations; seismic safety; economic evaluation; geotechnical and structural design

1. Introduction

Seismic events have accompanied mankind for many years and will continue to occur in the future. Due to their impact on society, they hold a relevant position in history. There are regions where earthquakes are more concentrated in quantity and intensity (Arriagada 2005). For UNESCO, the degree of threat in each region requires strict requirements in the design of constructions in relation to social responsibility and their level of development. The design of foundations in earthquake-prone areas requires special considerations. For shallow foundations, due to seismic loads, the bearing capacity decreases, while settlement and inclination increase (Richards, Elms, and Budhu 1993). The reduction in capacity will depend on soil type and terrain acceleration. The foundation of seismic zones must ensure the transmission of loads to the ground and allow for the verification of the assumed energy dissipation mechanisms of the superstructure (Paulay, Bachmann, and Moser 1990) with minimal damage, and building safety depends on these mechanisms. This leads to a foundation with high consumption of concrete and steel (Alvarez de Ulofi, Bella Fontaine, and Cabrera Castro, 2018), which would decrease for significant reductions in dead loads (Alvarez de Ulofi, 2019). Subsequently, geotechnical engineering and structural design were validated using linear dynamic time analysis (Alvarez de Ulov, Bella Fontaine, and Cabrera Castro, 2019), using synthetic seismic acceleration maps scaled for the building site, and providing important evidence for the seismic risk of the foundation.

In Cuba, research was developed to evaluate the calculation methods of geotechnical design of foundations (Chagoyén & Negrín 2009), which among others contributed to the "Cuban Standard for the Geotechnical Design of Superficial Foundations" (2016). This standard takes into account the decrease in soil bearing capacity caused by the inclination coefficient of seismic loads transmitted to the ground and the additional safety factor that reduces the total soil bearing capacity.

The total cost of civil engineering may change the way decisions or solutions are proposed, making this branch increasingly important. In earthquake prone areas, in order to determine what seismic risk mitigation measures to take, a quantitative analysis was conducted on the benefits and costs required to implement these measures based on the required performance level, in order to compare constructive alternative solutions and make scientifically reasonable investment decisions (Mora, 2015). The total cost of an earthquake zone can be expressed as the sum of various costs:

- Basic structural cost (low seismic hazard, gravity actions).
- Additional structural cost (guarantee seismic safety).
- Cost of non-structural elements (failure for seismic events).

The city of Santiago de Cuba experienced a major earthquake in 1932, with few casualties but severe damage. It is located in the area with the highest seismic risk in the country, and earthquake requirements dominate structural design. Reasonable structural projects are needed to ensure earthquake safety. They help to better utilize resources while avoiding serious economic and life losses, and mitigate negative and irreversible environmental impacts on the country. Therefore, due to the unknown additional cost of designing seismic ground foundations in different types and levels of structures in Santiago Province, Cuba, it undermines structural safety and introduces uncertainty in the estimation of project economic evaluations.

2. Materials and Methods

2.1 Geotechnical experimental investigations

It is assumed that the buildings under study are located in a geological engineering profile, where excavations were carried out up to 10 m depth. Experimental investigations of the physical-mechanical parameters in the soil strata encountered, carried out by Cabrera (2006) and published by Cabrera and Beira (2007), are summarized in Table 1 and Figure 1. The geological engineering soil profile is formed by a 3 m fill layer, followed by a clay layer of high compressibility (CH) up to 9 m and the a clay layer of low compressibility (CL). The average number of blows per foot (N_{SPT}) up to 7 m refer to a hard consistency, becoming very hard below this depth. Soil compression ratios (Cc) are between 0.14 and 0.22 and expansion ratios (Cs) are between 0.02 and 0.06. The foundations of the modeled buildings are deployed in the soil stratum CH, with a cohesion of 70 kPa, angle of internal friction of 15 degrees, submerged specific gravity 9 kN/m^3, average humidity 30%, average saturation degree of 80% and water table at 7 m.

Table 1. Average values of soil physical-mechanical parameters per meter depth (Cabrera 2006)

Est.	z (m)	LL (%)	LP (%)	Nspt (Golpes)	ω (%)	I_c	γ_l (kN/m³)	γ_d (kN/m³)	γ_s (kN/m³)	e_o	S (%)
R	1	64,5	25,6	15	23,6	1,1	18,3	14,8	26,9	0,70	79,0
R	2	63,1	24,6	22	24,4	1,0	19,3	15,5	26,9	0,62	69,0
R	3	56,5	24,4	16	25,6	1,0	18,6	14,8	26,6	0,72	76,0
1	4	60,3	24,6	29	29,8	0,9	18,5	14,2	26,8	0,72	85,0
1	5	56,9	28,2	21	35,8	0,7	17,8	13,1	26,8	0,92	83,0
1	6	81,7	31,8	20	34,0	1,0	17,8	13,3	26,9	0,84	90,0
1	7	80,3	30,8	21	41,9	0,8	16,8	11,9	27,2	1,29	88,5
2	8	74,3	27,6	23	22,3	1,1	18,2	14,9	27,3	0,84	75,0
2	9	54,2	24,5	22	20,4	1,1	19,6	16,2	27,4	0,69	83,0
3	10	49,4	24,2	58	19,7	1,2	20,3	17,0	27,2	0,60	90,7

Est: stratum; Nspt: average number of blows per foot; R: backfill; z: depth; LL: liquid limit; S: saturation; LP: plastic limit; ω: moisture Ic: consistency index; e_o: pore index; γl: specific weight of natural soil; γd: specific weight of dry soil; γs: specific weight of saturated soil).

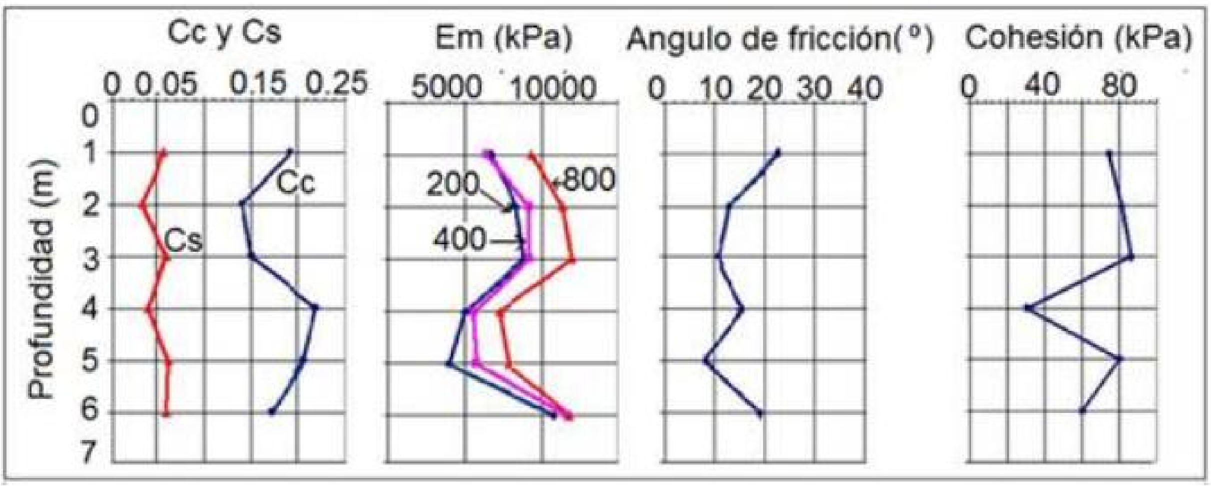

Figure 1. Compressibility and strength parameters of the soil profile up to 6 m depth (Cabrera 2006).

2.2 Structural model of the buildings analyzed

According to the Cuban seismic standard NC 46:2017 (2017), based on the physical and mechanical properties of elastic strata, a study was conducted on 5 low rise buildings, 4 residential buildings, and 1 social building constructed in soil profile D in Santiago, Cuba, with different floors and pillars (Table 2). For residential buildings, the drainage depth is 2.30 m, starting from a terrazzo factory located at a surface depth of -0.70 m, assuming that it is carried out for construction reasons before construction. For the social services of Building 5, the depth of Desplante should be considered as 3 m from the natural terrain height. The structure was modeled using SAP 2000 NL version 14. The load combinations used for basic design correspond to the recommendations of NC 450:2006 (2006) for wind and gravity loads, and NC 46:2017 (2017) for seismic loads.

Table 2. Data related to the geometry of the buildings and cross-sections of the substructure elements

Edif.	Dimensiones del Edificio				Elevación		Dirección Longitudinal Dir. X		Dirección Transversal Dir. Y	
	Altura (m)	Largo (m)	Ancho (m)	No. Pisos	Puntal Primer Piso (m)	Puntal Restantes Pisos (m)	No. Luces	Luz (m)	No. Luces	Luz (m)
1	8,4	30,0	10,2	3	3,0	2,70	10	3,0	2	5,1
2	12,3	15,0	7,8	4	3,3	3,00	5	3,0	2	3,9
3	9,3	14,4	8,4	3	3,3	3,00	4	3,6	2	4,2
4	5,7	24,0	10,2	2	3,0	2,70	8	3,0	2	5,1
5	16,5	36,0	30,0	5	3,3	3,30	5	7,2	5	6,0

Edif,	Dimensiones Viga Sísmica				Dimensiones Pedestal			
	Peralto (m)	Ancho (m)	A (m^2)	Ix (m^4)	Peralto (m)	Ancho (m)	A (m^2)	Ix (m^4)
1	0,80	0,30	0,2400	0,0128	0,55	0,55	0,3025	0,0076
2	0,65	0,25	0,1625	0,0057	0,50	0,50	0,2500	0,0052
3	0,70	0,25	0,1750	0,0071	0,50	0,50	0,2500	0,0052
4	0,70	0,25	0,1750	0,0071	0,50	0,50	0,2500	0,0052
5	0,90	0,40	0,3600	0,0243	0,60	0,60	0,3600	0,0108

A: Area of the cross-section; Ix: Moment of inertia with respect to the bending axis of the cross-section in the plane of the frames

Considering seismic loads, including vertical seismic requirements:

COMBO 1: CP + 25% CU+ 100% CSx + 30% CSy + 30% CSz

COMBO 2: CP + 25% CU + 30% CSx + 100% CSy + 30% CSz

COMBO 3: CP + 100% CSx + 30% CSy - 30% CSz

COMBO 4: CP + 30% CSx + 100%CSy - 30% CSz

COMBO 5: CP + CU

Considering wind load:

COMBO 1: CP + CU + CVx

COMBO 2: CP + CU + CVy

COMBO 3: CP + CVx

COMBO 4: CP + CVy

COMBO 5: CP + CU

Considering only gravity loads:

COMBO 1: CP + CU

Where:

CP: gravity loads including self-weight loads of the building structure

CU: building utilization loads

CS_X: horizontal seismic loads in the X direction of the building

CS_Y: horizontal seismic loads in the Y direction of the building

CS_Z: Vertical seismic loads

CV_X: Wind loads with predominant action in the X direction of the building

CV_Y: Wind loads with predominant action in the Y direction of the building

2.3 Load calculation methods

2.3.1 Seismic load

The seismic load is modeled using the "Equivalent Static Method" according to the Cuban seismic standard NC 46:2017, taking into account the three basic components of earthquakes, two horizontal components and one vertical component. 100% of the seismic load is combined in one of the main directions, while 30% of the seismic load is combined in the remaining directions. The vertical seismic load is modeled as an increase in the total permanent load, including the self weight of the structure, and is estimated to be 20% of the short-term response acceleration reference permanent load based on the design spectrum of the considered soil profile.

2.3.2 Wind load

The wind load modeling was performed by NC 285:2003 (2003) using the "Static Method", considering the wind action separately in the longitudinal (X direction) and transverse (Y direction) direction, for the basic wind pressure established for the eastern provinces in this regulation.

2.4 Surface foundation design

Three design variants of foundation slabs for five types of buildings were analyzed. The first variant considers the impact of earthquakes, the second variant considers the impact of wind, and finally only considers gravity loads. The foundation requirements provided in SAP 2000 NL version 14 have been exported to Excel Discar 3.0, which is based on current Cuban standards for geotechnical engineering and structural design of foundations. The size of the foundation plate with a rectangular pre-value of 1 should ensure that it meets the ultimate state of overturning stability, sliding, and bearing capacity. In order to evaluate the economic consequences of conservative use of the additional safety factors specified in Cuba's Shallow Foundation Geotechnical Design Standards (2016), the project considered three additional safety factors under normal geological conditions, namely 1.15, 1.20, and 1.25. The structural design uses G-40 steel (R_{ak} = 300MPa) and R'_{bk} = 25MPa concrete, and the diameter of the steel bars is changed according to the structural types of the three variants. We also checked the standards for shearing and perforation. Figure 2 shows the foundation floors and the types of foundations used in geotechnical and structural design.

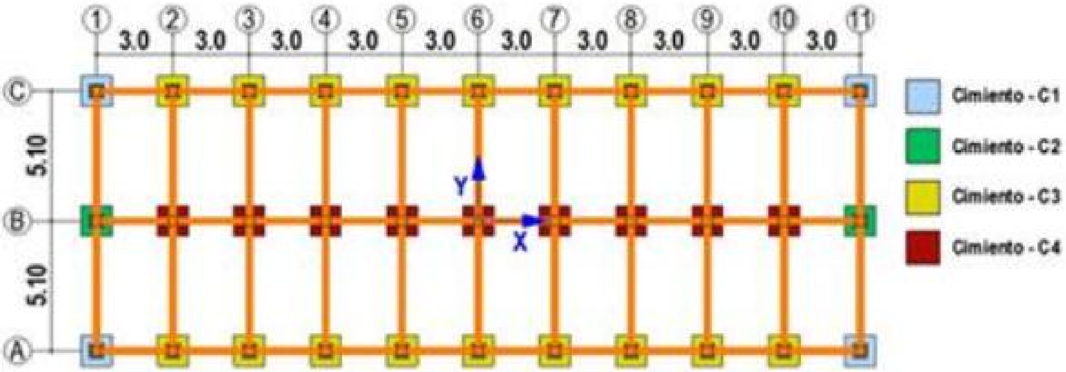

Figure 2. Foundation plan and types of foundations (Building 1).

2.5 Cost analysis

Once the dimensions of the foundations and the depth of the foundation in each case were defined, a direct cost analysis of the surface foundation (only plate) was performed, using the PRESWIN software for the calculation of budgets based on the construction price system in force in Cuba PRECONS II (2005). The excavated material was used as re-cast material and the cast-in-place concrete was considered to be made with washed sand from Juraguá and gravel from Los Guaos quarry. The prices of the materials (cement, steel, sand and stone) are those in effect according to current resolutions.

3. Results and Discussion

3.1 Calculation of ecological loads and gravity loads

The total horizontal seismic loads, wind loads for the two directions of wind action and total gravity loads at the soil base are summarized in Table 3.

Table 3. Total horizontal seismic loads, total wind loads for the two directions of wind action and total gravity loads at the base of soil

Cargas Sísmicas Horizontales Totales en la Base (kN)					
Edificios	1	2	3	4	5
Base	1639,15	859,76	534,75	778,59	6503,93
Cargas de Viento Horizontales en la Base del Edificio (kN)					
Dirección Viento					
Fachada	198,955	167,422	115,096	101,073	474,954
Combo Cálculo	278,531	234,390	161,134	141,502	664,936
Lateral	64,500	80,729	61,243	42,231	391,226
Combo Cálculo	90,301	113,021	85,740	59,124	547,716
Cargas Gravitatorias de Cálculo Totales en la Base (kN)					
Combo Cálculo	16171,73	8277,68	5401,94	7992,67	89214,90
Relación entre las cargas ecológicas y gravitatorias en la Base					
Edif.	CV fach/CS	CV Lat/CS	CV fach/CG	CV Lat/CG	CS/CG
1	0,1699	0,0551	0,0172	0,0040	0,1014
2	0,2726	0,1315	0,0283	0,0098	0,1039
3	0,3013	0,1603	0,0298	0,0113	0,0990
4	0,1817	0,0759	0,0177	0,0053	0,0974
5	0,1022	0,0842	0,0075	0,0044	0,0729

Facade: predominant wind action in the Y direction of the building; Lateral: predominant wind action in the X direction of the building

3.1 Geotechnical design of shallow foundations

Table 4 summarizes the dimensions (L = B) of the slabs for each variant and additional safety factor considered for each building foundation type. When seismic loads have an impact, these dimensions will significantly increase (over 30%), which will affect economic analysis. When seismic loads are included in the load combination, regardless of the type of building, the size of the foundation plate needs to be larger and does not vary significantly with additional safety factors.

Table 4. Variation of foundation dimensions offered by the geotechnical design for the domain of additional safety factors according to the Cuban standard for the geotechnical design of foundations

Edif.	Tipo de Cargas	γ_s	Dimensiones de los Platos de Cimentación (m)				
			C1	C2	C3	C4	Peralto
1	Sísmica	1,25	1,75	1,45	1,35	1,50	0,35
		1,15	1,75	1,45	1,35	1,45	0,30
	Viento	1,25	1,00	1,00	1,00	1,10	0,25
		1,15	1,00	1,00	1,00	1,00	0,25
	Gravitatorias	1,25	1,00	1,00	1,00	1,10	0,25
		1,15	1,00	1,00	1,00	1,00	0,25
2	Sísmica	1,25	2,05	1,50	1,60	1,45	0,35
		1,15	2,05	1,50	1,60	1,40	0,30
	Viento	1,25	1,00	1,00	1,00	1,10	0,25
		1,15	1,00	1,00	1,00	1,00	0,25
	Gravitatorias	1,25	1,00	1,00	1,00	1,00	0,25
		1,15	1,00	1,00	1,00	1,00	0,25
3	Sísmica	1,25	1,65	1,35	1,25	1,30	0,35
		1,15	1,65	1,30	1,25	1,25	0,30
	Viento	1,25	1,00	1,00	1,00	1,00	0,25
		1,15	1,00	1,00	1,00	1,00	0,25
	Gravitatorias	1,25	1,00	1,00	1,00	1,00	0,25
		1,15	1,00	1,00	1,00	1,00	0,25
4	Sísmica	1,25	1,35	1,20	1,10	1,20	0,35
		1,15	1,35	1,20	1,10	1,15	0,30
	Viento	1,25	1,00	1,00	1,00	1,00	0,25
		1,15	1,00	1,00	1,00	1,00	0,25
	Gravitatorias	1,25	1,00	1,00	1,00	1,00	0,25
		1,15	1,00	1,00	1,00	1,00	0,25
5	Sísmica	1,25	2,85	2,45	2,55	2,65	0,55
		1,15	2,85	2,35	2,45	2,60	0,55
	Viento	1,25	1,60	1,85	1,90	2,30	0,55
		1,15	1,60	1,80	1,85	2,20	0,55
	Gravitatorias	1,25	1,60	1,85	1,90	2,25	0,55
		1,15	1,60	1,75	1,80	2,15	0,55

3.2 Cost analysis

Figure 3 shows the direct total cost of each building under each load type (vertical, wind, and earthquake) and the results of the additional safety factors analyzed. The cost difference between variants that consider or do not consider seismic effects is significant, exceeding 34%, which confirms that in seismic design, the consumption of materials (concrete and steel) will be greater. There was no significant difference in cost under the influence of gravity and wind loads (Table 5).

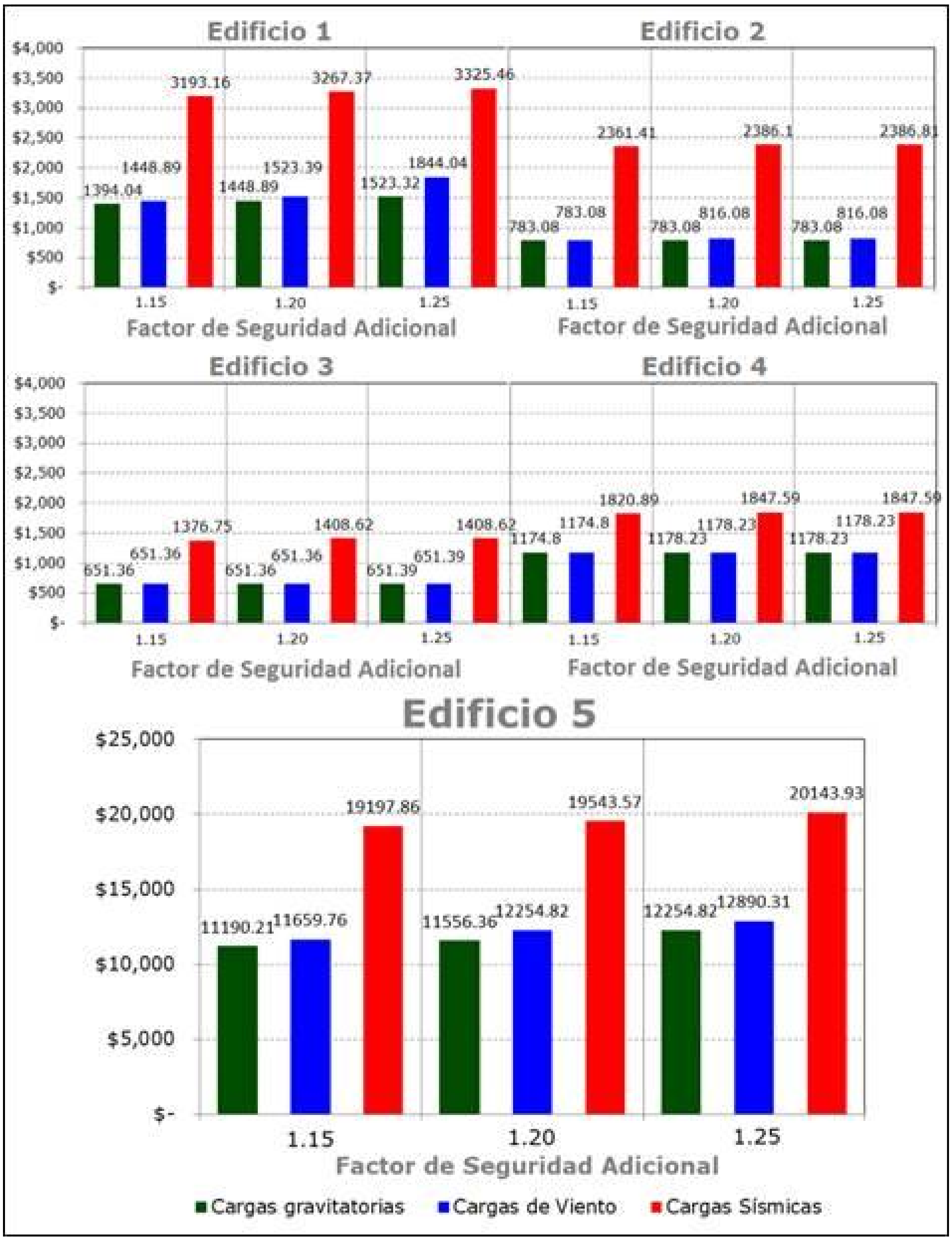

Figure 3. Comparison of direct foundation costs for the analyzed loads and additional safety factors according to the Cuban standard for the geotechnical design of shallow foundations.

Table 5. Increase in total direct foundation costs due to wind and seismic loads relative to gravity loads (s = 1.15)

Edificios	Costos Totales ($)			Incremento de Costos Totales vs. Cargas gravitatorias (%)	
	Cargas Gravitatorias	Cargas de Viento	Cargas Sísmicas	Cargas de Viento	Cargas Sísmicas
1	1394,04	1448,89	3193,16	3,79	56,34
2	783,08	783,08	2361,41	0,00	66,84
3	651,36	651,36	1376,75	0,00	52,69
4	1186,63	1186,63	1820,89	0,00	34,83
5	11190,21	11659,76	19197,86	4,03	41,71

The similar dimensions of the foundation plates due to wind loads and gravity loads are controversial, generating similar costs, which is justified below:

- According to the Cuban wind load standard, the basic wind pressure in the eastern provinces (0.9 kg/m^2) is much lower than that in the central provinces (1.1 kg/m^2) and western provinces (1.3 kg/m^2), with a maximum sustained wind speed of 136.6 km/h, far lower than the recent strong hurricane that hit the country. The studied building did not reach a significant height and had a low wind speed gradient. In addition, for basic design, wind load rules do not consider gust coefficients as their effects dissipate in the upper structure.
- Reinforced concrete buildings designed to withstand earthquakes are heavy because of the use of flat slabs and large cross sections of beams and columns, which guarantee reduced relative displacements of the floors for damage control. The foundation is recommended to be rigid, using seismic pedestals and beams with large cross sections and moments of inertia in the bending plane of the portal frames. The residential buildings (Buildings 1 to 4) also have floor plan modulations, which do not result in large spans, so that the intercolumns in the facades will also be reduced. All of the above determines that wind loads transmit reduced overturning moment and sliding forces to the isolated footings compared to those caused by seismic loads.
- The structural modeling for wind loads assumes linear elastic behavior of the structure, so the effective width of the beam flanges integrally fused with the slabs is much greater than for the elasto-plastic behavior model assumed for seismic loads. This determines that the beam is more involved in the bending of the gantry, thereby reducing the overturning moment reaching the foundation plate.
- The calculation combination of maximum gravity load used for geotechnical design of foundation slabs incorporates significant control factors, especially those used for load usage, in order to determine the vertical load transmitted to the ground, which is of great significance for the geotechnical design of isolation gates. Conversely, when combining the gravity load with the wind load, the resulting value approaches the magnitude of the maximum gravity load combination. However, due to the relatively smaller wind load, the torque transmitted to the insulation brake shoe is minimal. Consequently, it is determined that the eccentricity of the vertical load transmitted to the insulation brake shoe is negligible and will not have a significant impact on its geotechnical design

By comparing the costs of gravity and seismic loads, a significant increase (34% to 66%) can be observed, as shown in Table 5 and Figure 4. By changing the additional safety factor (γ_s) of the same building, including seismic loads, the foundation cost of some buildings may slightly increase (Figure 4), especially in the case of building 1 and 5 models.

Figure 4. Increases in direct foundation costs due to seismic loads and variation of direct costs as a function of the selected additional factor of safety.

4. Conclusions

Earthquake loads dominate the geotechnical design of slabs, and their size significantly increases compared to wind or gravity loads. The increment is independent of the position of the foundation floor, and there is almost no change in the selected additional safety factor. The cost of foundation plates in low-rise reinforced concrete buildings studied in Santiago, Cuba, caused by seismic loads, is much higher than that caused by wind and gravity loads (ranging from 34% to 66% higher). There is a significant difference in the cost of foundation plates for gravity and wind loads. Therefore, the additional cost of earthquake safety can be estimated based on the gravity load of low rise reinforced concrete buildings built in Santiago, Cuba.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Notes

ERAD: Structural modeling of the analyzed building variants using SAP 2000. Obtaining the calculation stresses in the foundations. Geotechnical and structural design of the foundation plates.

MDM: Structural modeling of the analyzed building variants using SAP 2000. Obtaining of the computational stresses in the foundation. Geotechnical and structural design of the foundation plates.

EBF: Geotechnical experimental investigations. Definition of the geological engineering soil profile and determination of the physical-mechanical soil parameters used in the design of the foundation plates.

PMCC: Geotechnical experimental investigations. Definition of the geological soil engineering profile and determination of the soil physico-mechanical parameters used in the design of the foundation plates.

All authors worked equally in data processing, interpretation of results and elaboration and final approval of the article.