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VARIATION STUDY OF THE CONSTRUCTION COST OF A 15-STORY R/C BUILDING BASED ON THE SEISMIC RISK ZONE

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Abstract

Greece is divided into three seismic hazard zones ZI, ZII, ZIII. In the present research work, the same building in the three seismic zones of Greece is modeled, analysed and dimensioned and then the construction cost of its structural body is estimated. The building modeling was performed in SAP2000 using linear finite elements. The analysis of the building was performed by dynamic spectral analysis methods using the design spectrum of EC8. A fifteen-storey building with a standard floor plan per floor was used. The dimensioning of the building took place based on the results of the ground floor. The purpose of this research paper is to study the possible influence of seismicity, based on which the dimensioning takes place, on the construction cost of the load-bearing structure of a fifteen-storey building with a standard floor plan per floor. The degree of influence is studied by estimating the quantities of materials required depending on the seismic hazard zone. Interesting comparisons take place between the results for the three different seismic hazard zones. Useful conclusions are drawn regarding the influence of seismicity on the construction cost of the load-bearing structure of reinforced concrete buildings.

Keywords: Cost of construction, Seismicity, Seismic hazard zone

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1 INTRODUCTION

A catalytic role for the success of a project is played by an accurate construction cost estimation [1]–[7]. Construction cost means the cost made up of the purchase value of the materials and the labor fee that can be offered directly or through a subcontractor. For construction cost management to be considered successful, it is necessary to process certain processes such as resource planning, cost estimation, cost budgeting and its control. These processes aim to provide a construction cost estimate to guide a budget in order to complete the project within the given budget timeframe [8]. The size, construction area, density of columns and beams, the seismicity of the area and the type of foundation are some of the factors that affect the final construction cost [9]–[18]. As can be understood from the title, the present research work has as its main object of interest the seismicity and its influence on the construction cost, which is why special emphasis is placed on the term "seismicity". In more detail, an earthquake is a phenomenon, which usually occurs without any warning, it is an inevitable phenomenon and despite the fact that it lasts a short period of time, it is capable of causing significant material damage to human infrastructure, resulting in serious injuries and even loss of human life [19]. The term seismicity has no specific definition. It can be rendered as an increasing function of both the magnitudes and the frequency of them in an area during a certain period of time. Still, it depends on the size interval for which it is considered. The term seismic hazard is defined as the maximum expected value of a seismic parameter for a given recurrence period or for a specific probability of non-exceedance and a specific period of time [20]–[23].

The Map of Seismic Hazard Zones of Greece that is valid today was designed in the period 1986-1989 and started to be implemented in 1995. Its revision, almost 15 years after its preparation, was deemed necessary for many factors that have intervened since then. With the new map, the Greek area is divided into three zones of seismic risk, in contrast to the four zones, depending on the seismic risk, into which it was divided until now, as the smaller one is removed (Figure 1) [24]. The design ground acceleration values are 0.16g (percent of the acceleration of gravity g) for the first zone, 0.24g for the second zone and 0.36g for the third zone (Table 1) [24]. According to statistics, in terms of seismicity, Greece ranks first in the Mediterranean and in Europe, as well as sixth globally. Each earthquake has its own identity defined by physical characteristics, induced phenomena and effects. The physical characteristics of an earthquake are its magnitude, point (epicenter) and time of occurrence, as well as the extent to which it was felt locally. The two main regulations with which the dimensioning of the building of this research work complies are the Greek Seismic Code [24] and the Eurocodes [25]–[27]. More specifically, starting with the first one as its primary objectives, the regulation sets the protection of human life in the case of high intensities, the limitation and even the avoidance of economic losses in the case of moderate intensities. Finally, the assurance of a minimum level of operations of the projects. The projects covered by the regulation are the so-called "normal risk", i.e., projects whose potential damage is limited to the project itself, its contents and its immediate vicinity. The regulation consists of the basic provisions, design criteria, seismic actions and provisions related to the soil and supports applied to buildings and other structures in seismic areas. For projects such as bridges, silo tanks as well as the strengthening of existing buildings, additional provisions are necessary [28]–[31]. The same is provided for projects involving partial or complete anti-seismic insulation. This regulation offers options to the practitioner who is willing to implement more precise calculations than those required in everyday practice applications.

Zone of seismic risk	Ground acceleration values (g)
Z1	0,16
Z2	0,24
Z3	0,36

Table 1: Ground acceleration values [24].

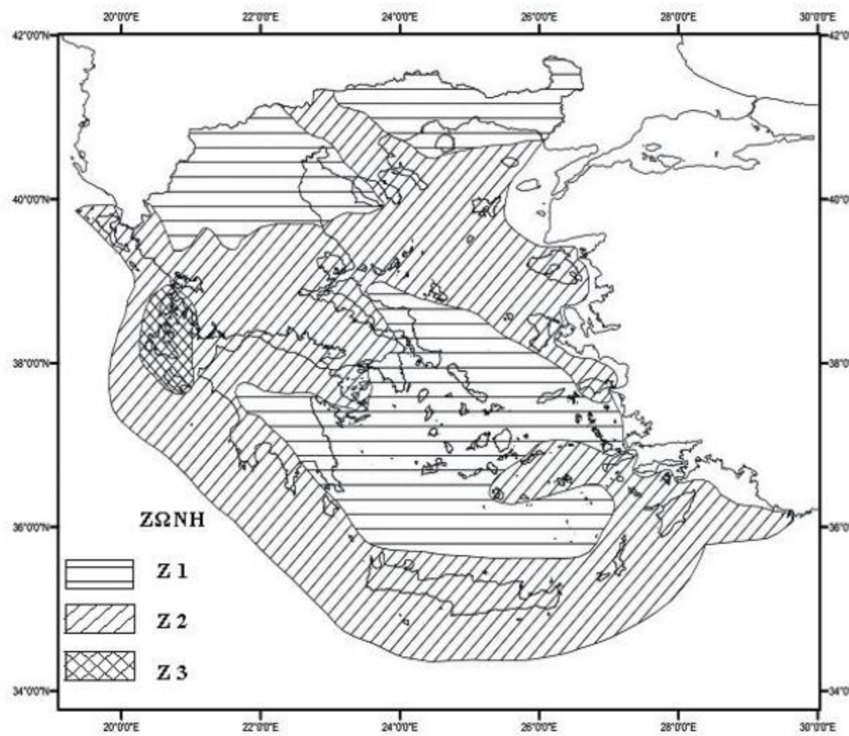


Figure 1: Seismic hazard map of Greece [24].

It is important to emphasize that in order to accept the application of the most accurate methods, it is necessary to satisfy certain conditions, to be accompanied by sufficient proofs that make them reliable and to ensure a level of safety at least commensurate with that intended by this regulation and in any case subject to the approval of their use by the competent public authority. Seismic risk is considered to be adequately addressed by the design, construction and use of a structure. This means that the elements of the load-bearing body under the design earthquake ensure minor and repairable damages [32]–[38]. Furthermore, they minimize the damages for earthquakes of lower intensity and with a higher probability of occurrence, when imposing the "design" seismic actions with an acceptably small probability of exceeding them during the life of the structure [39], [40]. With the flexural yielding of critical areas, i.e., the formation of plastic joints, the load-bearing body is able to turn into an elasto-plastic mechanism, which continues to respond to the peaks of seismic movements with practically constant intensity, releasing in each cycle a significant part of the seismic energy it has absorbed [20], [32], [34], [41]–[44]. The reduction of the calculated seismic action to a fraction 1/q of that corresponding to an elastic response is achieved by this capacity of the load-bearing body ("ductility"). This has the effect of limiting the resulting economic burden from seismic design to a reasonable framework. At the same time, it makes less pronounced the consequences of the various uncertainties arising from the seismic design. In order to achieve sufficient ductility of the load-bearing body, a reliable plastic mechanism without risks of cracking or chain collapse and a minimum degree of local ductility of the critical areas must be ensured through competent design with appropriate concrete confinement [20], [34], [45], [46]. At this point it is important to clarify the term "ductility", by the term ductility, it is meant the ability of the structure to absorb seismic energy and develop plastic deformations without significant loss of lateral strength and axial load carrying capacity (not to collapse).

As already mentioned, one of the regulations that this research work focuses on is the Eurocodes. The Eurocodes consist of a series of ten European Standards for the design of structures developed by the European Committee for Standardization. In this paper, a more extensive reference will be made to Eurocode 8 [25], as its subject is the anti-seismic design of load-bearing structures. The first part of Eurocode 8 presents the general requirements for seismic behavior as well as the rules for determining the seismic action for the design of any type of project. It mainly focuses on the compliance criteria and special rules for steel, reinforced concrete, wood or load-bearing masonry, composite (steel and concrete) buildings, as well as seismically insulated buildings. An extreme scenario is the case where the load-bearing body is required to remain elastic to the imposed deformations based on its strength alone. This results in a requirement of at least equal strength to the horizontal forces introduced by the earthquake into the elastic load-bearing body, based on its mass and elastic stiffness. In the Greek area, these forces receive values of 40% to 90% of the total weight of the project. Even if it is technically possible to design the load-bearing body in such a way that it is able to remain elastic under these forces, it is an extremely uneconomical solution for the load-bearing body and its foundation.

In the Greek region, it was fully embraced for buildings with concrete supports, that it is allowed to design the support for an elastic response to the design seismic action and indeed by dividing the elastic horizontal forces with a behavior factor of q=1.5 instead of q=1.0 which corresponds to elastic behavior. This is done by taking into account overstrength, such as margins between average design values and design values of material strengths, overstrength offered by minimum reinforcements or design for non-seismic actions. According to Eurocode 8 [25], the basic method of anti-seismic design and the only one accepted in the Greek area for buildings with concrete structures, is based on ductility. In Eurocode 8 [25], certain guiding principles are recorded and analyzed, from which it is necessary to shape the body of the building, in order to satisfy the basic behavior requirements at an acceptable cost. Indicative of some of these principles are the static simplicity, the uniformity and symmetry of the load-bearing body.

2 ANALYTICAL RESEARCH

2.1 Building data

The object of this work is the study of a 15-story reinforced concrete structure for all three seismic hazard zones. In more detail, the construction is doubly symmetrical, it has a rectangular floor plan measuring 25×25m with no basement (Figure 2). Additionally, in the center of the floor plan is a strong core, which is made up of a total of eight walls of different dimensions (six along the Y-axis and two along the X-axis). Finally, there are two walls at the perimeter of the plan along the Y-axis, whose edges have hidden columns. The cross-sections of the building's columns remain constant for the 1st floor (ground floor) and the 2nd, while the rest of the cross-sections of the columns are reduced by 5 cm per floor. At the same time, the cross-sections of the beams remain constant at all floors, in contrast to the cross-sections of the walls, which vary throughout the height of the building and, more specifically, they decrease by 12.5 cm every five floors. The load-bearing body's modelling has been performed with the usage of SAP2000 analysis software. The construction materials of the load-bearing body, which are C30/37 for the concrete and B500C for the reinforcement steel, are included in the program. According to the EC2 regulation [26] for concrete class C30/37, the modulus of elasticity is taken as E_{cm}=32 GPa, the self-weight of concrete γ_c=25 kN/m^3, the value of Poisson's ratio is taken as zero according to the specifications of the code for cracked concrete sections ν=0. From the sequence of commands in the program, the materials and the cross-sections of the structural elements (beams, columns, walls) are defined.

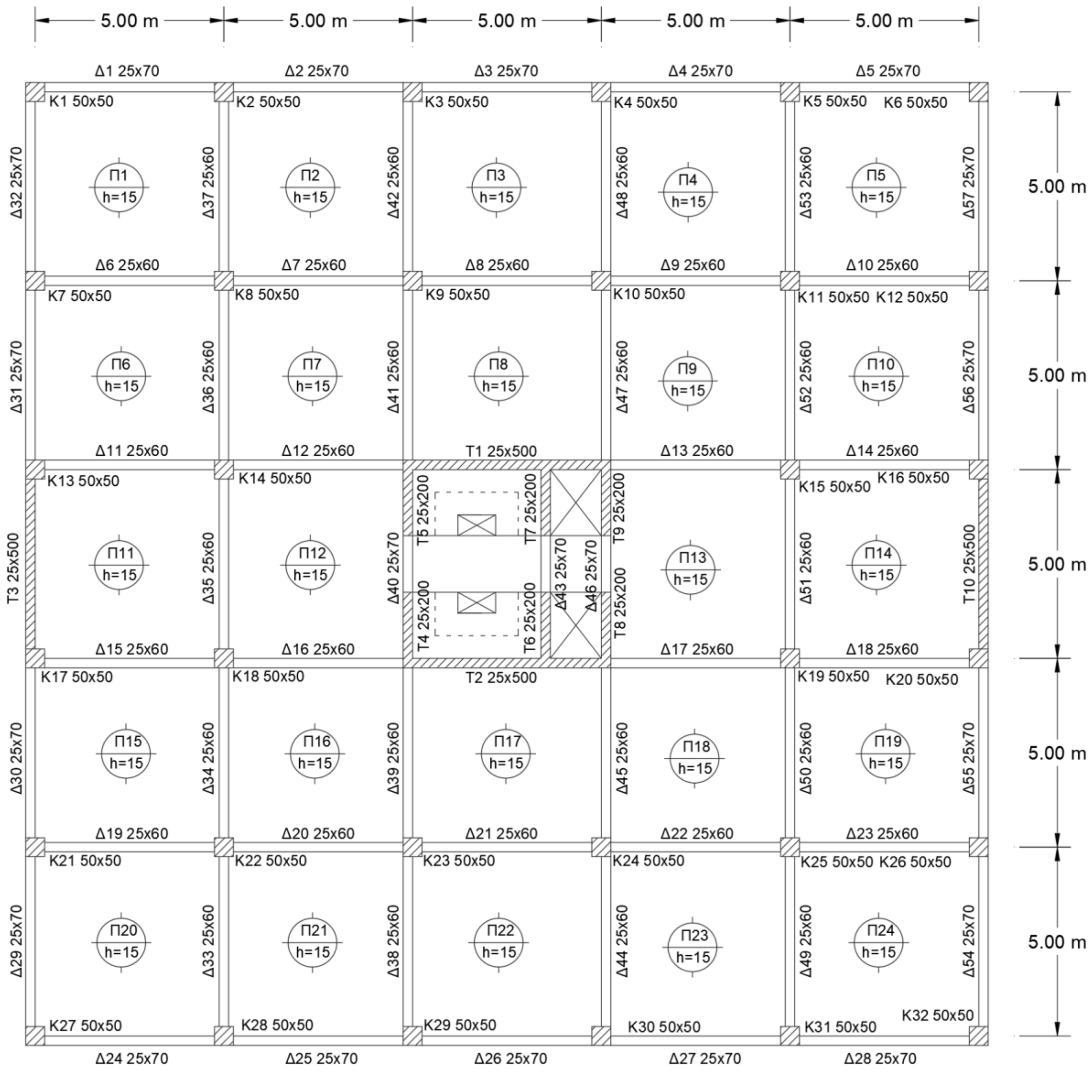


Figure 2: Typical floor plan.

Floor	Height (m)	Beam dimensions (cm)		Wall thickness (cm)	Column dimensions (cm)
		Perimetric	Internal		
1st (Ground floor)	4.50	25×70	25×60	50	100×100
2	3.00	25×70	25×60	50	100×100
3	3.00	25×70	25×60	50	95×95
4	3.00	25×70	25×60	50	90×90
5	3.00	25×70	25×60	50	85×85
6	3.00	25×70	25×60	37.5	80×80
7	3.00	25×70	25×60	37.5	75×75
8	3.00	25×70	25×60	37.5	70×70
9	3.00	25×70	25×60	37.5	65×65
10	3.00	25×70	25×60	37.5	60×60
11	3.00	25×70	25×60	25	55×55
12	3.00	25×70	25×60	25	50×50
13	3.00	25×70	25×60	25	45×45
14	3.00	25×70	25×60	25	40×40
15	3.00	25×70	25×60	25	35×35

Table 2: Dimensions of the structural elements.

2.2 Loads

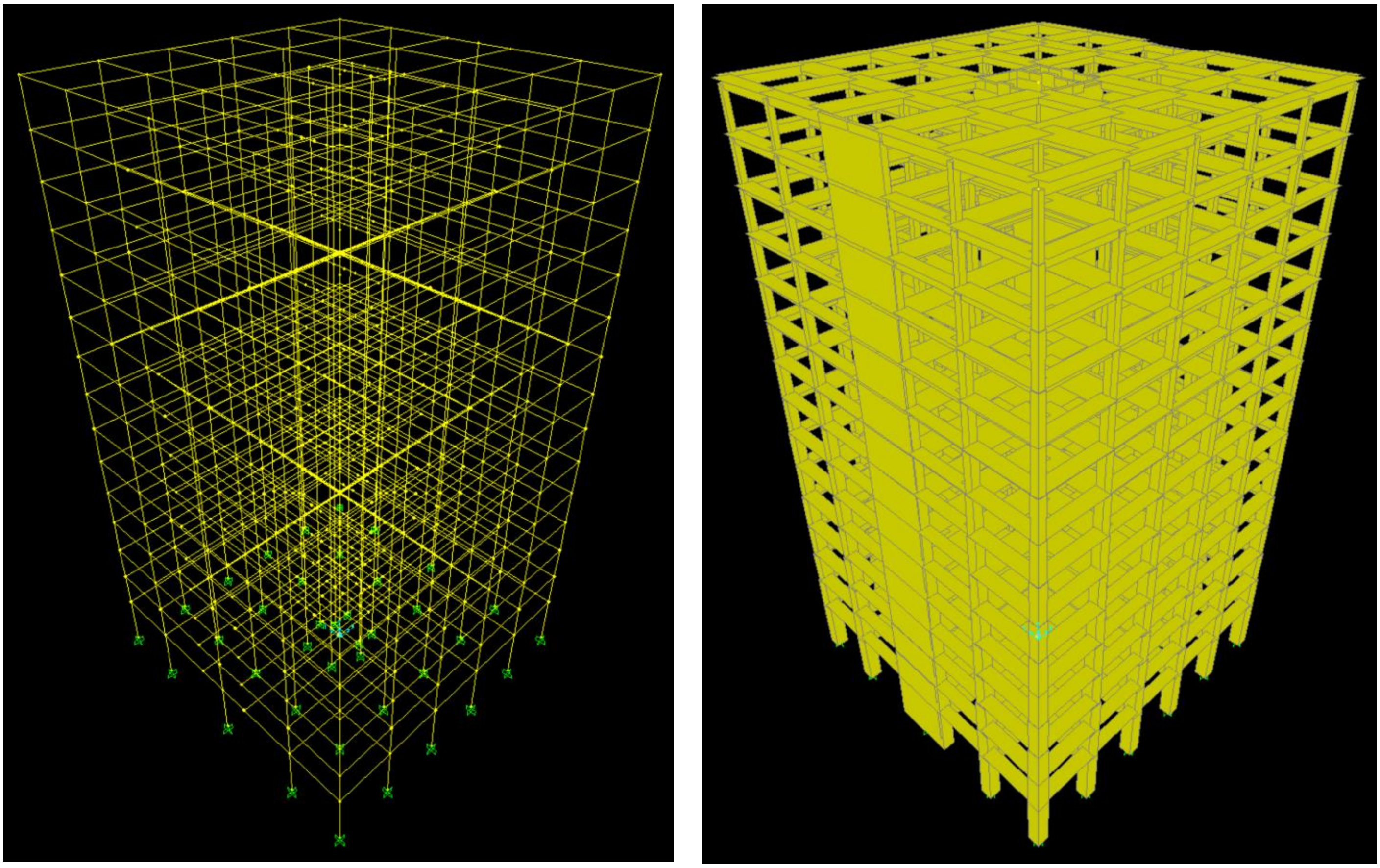
For the building in question, the loads are shown in Table 3.

PERMANENT LOADS		
N/A	**Type**	**Value**
1	Flooring	1.40 kN/m^2
2	Partition brick structures	1.00 kN/m^2
3	Perimeter brick structures	8.00 kN/m
4	Roofing	3.50 kN/m^2
5	Parapet roof load	3.60 kN/m^2
LIVE LOADS		
N/A	**Type**	**Value**
1	Ground floor	2.00 kN/m^2
2	Typical floors	2.00 kN/m^2
3	Roof	2.00 kN/m^2
SPECTRUM DATA EC8		
N/A	**Type**	**Data**
1	Spectrum type	Horizontal design spectrum type 1
2	Soil category	B
3	Factor β	0.20
4	Seismic acceleration factor α	For the three categories: α =0.16, 0.24, 0.36
5	Gravity acceleration g	9.81 m/sec^2
6	Coefficient behavior q	Calculation based on EC8

Table 3: Building loads.

2.3 3D Modelling

The 3D modelling of the building is presented at Figure 3. The display takes place both for linear finite elements and the sections of the building.



(a) (b)

Figure 3: Views of the 3D building model: (a) Linear finite elements (b) Sections.

2.4 Measurements of building materials

Based on the data obtained from the program for all three seismic hazard zones (stresses) the dimensioning of the load-bearing body for the structural elements of the ground floor was carried out. After a series of calculations, tables were formed with the bending and shear reinforcements for all three seismic hazard zones, for the structural elements (slabs, beams, columns, walls).

As already pointed out, the pre-measurement of the materials required for the construction of the project is an effective method in order to obtain as accurate a cost estimate as possible in order for the project to be successful. After all the necessary elements from the dimensioning have been gathered, the pre-measurement takes place. Initially, the pre-measurement of the concrete was carried out in all three zones, which were studied. It was observed that the amount of concrete remains constant for the three seismic zones, due to the fixed dimensions of the structural elements.

CONCRETE MEASUREMENT					
STOREY	SLABS (m^3)	BEAMS (m^3)	COLUMNS (m^3)	WALLS (m^3)	TOTAL (STOREY) (m^3)
1	90	33.08	139.2	63.08	325.36
2	90	33.08	91.2	41.33	255.61
3	90	33.92	82.31	41.61	247.84
4	90	34.72	73.87	41.90	240.49
5	90	35.55	65.89	42.18	233.62
6	90	36.35	58.37	31.85	216.57
7	90	37.19	51.3	32.06	210.55
8	90	37.99	44.69	32.28	204.96
9	90	38.82	38.53	32.49	199.84
10	90	39.62	32.83	32.7	195.15
11	90	40.46	27.59	21.95	180.00
12	90	41.26	22.8	22.09	176.15
13	90	42.09	18.47	22.23	172.79
14	90	42.89	14.59	22.37	169.85
15	90	43.69	11.17	22.52	167.38
				TOTAL	**3196.16**

Table 4: Concrete measurement.

3 RESULTS ANALYSIS

Below are pie charts where the results were analyzed with their help (Figure 4, Figure 5).

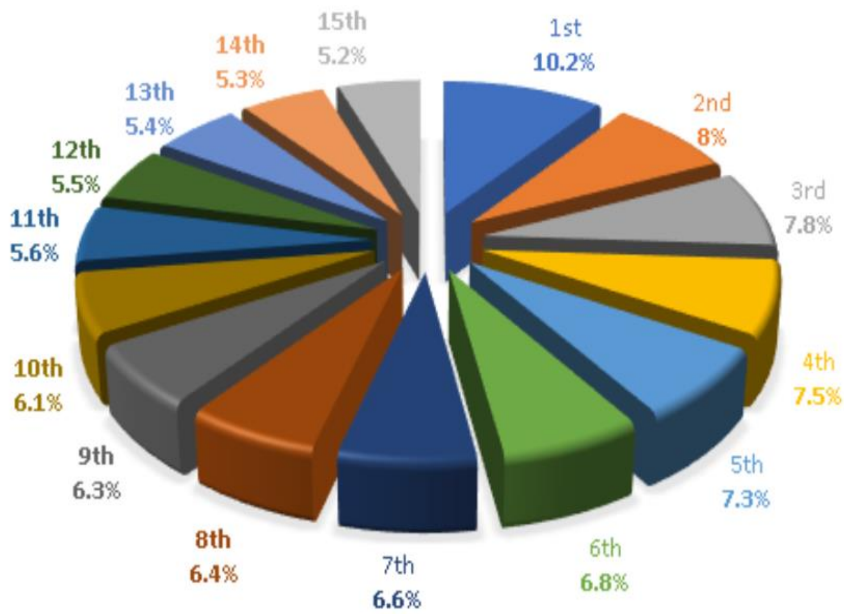


Figure 4: Percentage of concrete per floor (%).

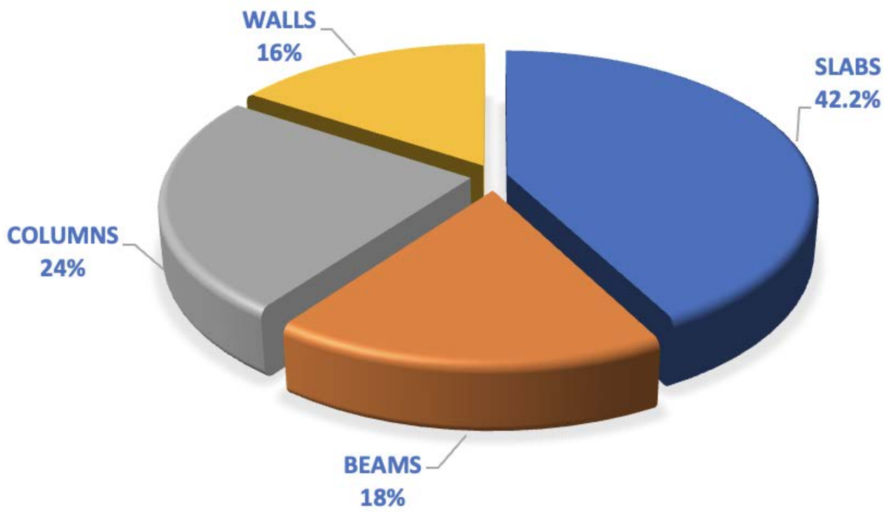


Figure 5: Percentage of structural elements in total concrete (%).

According to the pie diagram of Figure 4, it can be seen that the 1st floor occupies a larger percentage of concrete, compared to the other floors. On the contrary, the percentage of the remaining floors decreases from floor to floor (Figure 4). Still, the slabs are the ones that occupy the largest percentage of the total concrete with a percentage of 42.2%, followed by the columns with a percentage of 24%, the beams with a percentage of 18% and finally the walls with a percentage of 16% (Figure 5). Continuing with the analysis of the ground floor structural element reinforcement results for all three seismic zones, a diagram of the structural element reinforcement weight follows (Figure 6).

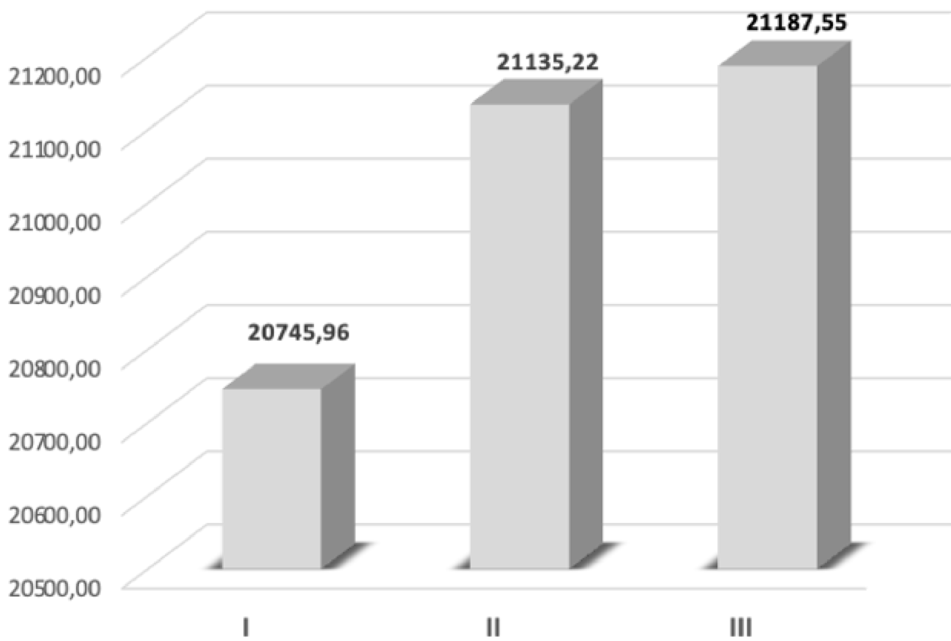


Figure 6: Total steel weight of ground floor structural elements for each seismic zone.

Then, a diagram was formed with the percentage increase in the total steel weight of the structural elements (Figure 7).

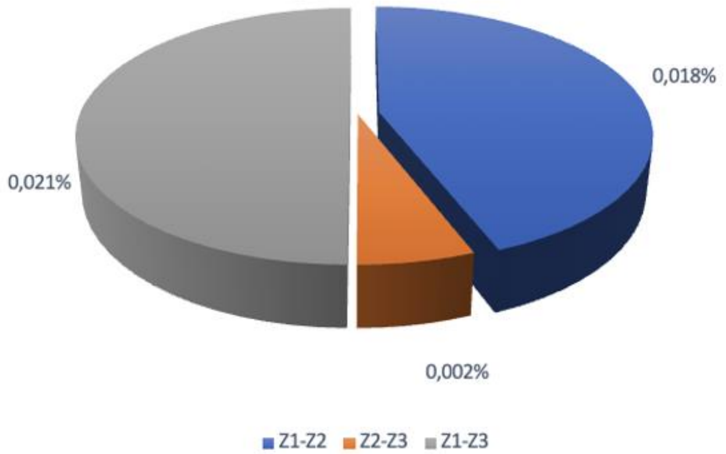


Figure 7: Percentage increase in total steel weight of ground floor structural elements between zones.

Through the preceding diagrams, the following emerges:

1. The transition of the structure from Zone I seismic acceleration α_g = 0.16g to Zone II seismic acceleration α_g = 0.24g results in:
   - 1.8% increase in the total steel weight of all structural elements
   - 0.3% increase in column steel weight
   - 1% increase in beam steel weight
   - 1.1% increase in wall steel weight
2. The transition of the structure from Zone II seismic acceleration α_g = 0.24g to Zone III seismic acceleration α_g = 0.36g results in:
   - 0.2% increase in the total steel weight of all structural elements
   - 0.29% increase in column steel weight
   - 0.59% increase in beam steel weight
   - 0.2% increase in wall steel weight
3. The transition of the structure from Zone I of seismic acceleration α_g = 0.16g to Zone III of seismic acceleration α_g = 0.36g results in:
   - 2.1% increase in the total steel weight of all structural elements
   - 0.6% increase in column steel weight
   - 1.57% increase in beam steel weight
   - 1.1% increase in wall steel weight
4. The increase in seismic acceleration by:
   - Zone I to Zone II: ((0.24-0.16)/0.16)*100 = 50 => 50% increment
   - Zone II to Zone III: ((0.36-0.24)/0.24)*100 = 50 => 50% increment
   - Zone I to Zone III: ((0.36-0.16)/0.16)*100 = 125 => 125% increment
5. There is an increase in the percentage of the weight of the individual structural elements of the structure (columns, beams and walls) from Zone I to Zone II and Zone III, except for the percentage of slabs, which remains constant for all three zones. This results in an increase in the total weight of the ground floor steel considered. More specifically:

- The slabs occupy certain percentages in steel, e.g. in Zone I: 44%, then in Zone II: 43% and lastly in Zone III: 43.5%.
- The beams occupy certain percentages in steel, e.g. in Zone I: 30%, in Zone II: 30% and in Zone III: 30%.
- The columns occupy certain percentages in steel, e.g. in Zone I: 12.3%, in Zone II: 12.4% and in Zone III: 12.4%.
- The walls occupy certain percentages in steel, e.g. in Zone I: 12%, in Zone II: 13.6% and in Zone III: 13.6%.

6. Also, it appears that during the transition from one zone to another for all three seismic zones:

➢ While the beams keep their longitudinal reinforcement constant, the transverse reinforcement shows some increments.
➢ The columns also keep their longitudinal reinforcement constant, while the transverse reinforcement shows some increments.
➢ Finally, the walls show increments in their transverse reinforcement, while at the same time the T3-T10 walls also show increments in their longitudinal reinforcement.

4 CONCLUSIONS

The building of the present study consists of 15 floors, is made of reinforced concrete with no basement and has a rectangular conventional floor plan in the three seismic zones Z1, Z2, Z3.

The conclusions reached in summary are the following:

1. Beams show the largest percentage increase in steel weight with increasing seismic acceleration.

Specifically during the transition:

➢ From Zone I (0.16g) → Zone II (0.24g): Increases 1%
➢ From Zone II (0.24g) → Zone III (0.36g): Increases 0.6%
➢ From Zone I (0.16g) → Zone III (0.36g): Increases 1.57%

2. In walls steel increases less than beams:

➢ From Zone I (0.16g) →Zone II (0.24g): Increases 1.1%
➢ From Zone II (0.24g) → Zone III (0.36g): Increases 0.2%
➢ From Zone I (0.16g) → Zone III (0.36g): Increases 1.1%

3. In columns the steel increases even less than in walls:

➢ From Zone I (0.16g) →Zone II (0.24g): Increases 0.3%
➢ From Zone II (0.24g) →Zone III (0.36g): Increases 0.29%
➢ From Zone I (0.16g) →Zone III (0.36g): Increases 0.6%

4. So, it follows that the dominant position in our structure is occupied by the beams.

5. The increase in seismic acceleration α_g:

- From Zone I → Zone II it is of the order of 50%, while the percentage increase in the total amount of materials quantifies to only 1.8%.
- From Zone II → Zone III is of the order of 50%, while the percentage increase in the total amount of materials is only 0.2%
- From Zone I →Zone III is of the order of 125%, while the percentage increase in the total amount of materials quantifies to only 2.1%.

6. Therefore, the percentage increase in total steel demand is quite small.
7. According to all the above, it comes to the conclusion that for a fifteen-story reinforced concrete building, with a strong wall core arrangement, the influence of the seismic risk on the construction cost of the building is not an important factor, since the percentage increase of the materials required is quite smaller compared to the large percentage increases of the corresponding seismic accelerations.

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