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ECONOMIC DESIGN OF FOUNDATION OF EARTHQUAKE-RESISTANT R/C BUILDINGS

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ABSTRACT

In the context of the present work, which can be characterized as multi-parametrical, the possibilities of reducing the consumption of materials and in particular of concrete are considered. It is tried to be found from the theoretically existing infinite geometry solutions, those which provide the more economical solution based on the actual values of concrete and steel, based on the normally acceptable and constructively achievable values of the geometric parameters. Moreover, the present work considers, as different cases of bearing body structure, the number of floors, beam spans, seismicity, wall stiffness, column cross-sections, the existence or not of the basement and the type of foundations.

1. INTRODUCTION

The dimensioning of load-bearing structures is governed by a wide range of compliance criteria, which are related to safety, functionality, economy, aesthetics, durability, manufacturing convenience, maintenance needs, etc. In particular, in earthquake-proof structures, the economic issue is mainly influenced by the basic idea of their design, ie the choice of the best-performing load-bearing structure depending on its case [1]. From the structural members for which the earthquake loading proves critical in their sizing, e.g. the walls, the columns, the beams and the foundation, the economics is an interesting problem for consulters, which has not been systematically examined until today. Besides, it is not a main issue for modern codes [2, 3].

The present study examines analytically different cases of structural elements and foundations. The main conclusion of this work is that the economics is closely linked to the parameter of the mechanical reinforcement ratio of the structural elements. However, the data examined do not all of them show the same degree of receptivity as regards the pursuit of economy and, where appropriate, other criteria, such as aesthetics, functionality or security, prevail over the criterion of the economy.

2. DESIGN FACTORS FOR LOAD-BEARING STRUCTURES

The design of load-bearing bodies is governed mainly by the fact that their overriding function is their ability to bear loads, vertically and horizontally (gravity, earthquake, etc.) [4]. The choice of optimal system is influenced by the prior architectural design and by the manufacturing methods to be applied [5]. However, consideration of the structure's seismic behavior proves sometimes very often decisive for the whole bearing structure and critical for some highly stressed members due to earthquake action [6].

It is known that the construction studies must meet both specific service requirements with respect to their use, and construction-related requirements relative to their construction method. Beyond these, the main factors of their design are: (a) Safety, (b) Functionality, (c) Economics (of construction and maintenance), and (d) Aesthetics. The criteria relating to safety and functionality are determined by codes, which reflect the current views with regard to design of load-bearing bodies. Structural security and functionality is the subject of Civil Engineer work, which works by applying correct principles that are generally established and accepted.

The cost of a particular building can be determined based on both experience and according to case studies. Certainly the cost depends on the basic idea of the study, meaning the choice of the load-bearing system. The basic concept of design includes not only the general idea of overall construction but also the idea of structural members and construction details. In this sense the basic concept of design is the most important, the most interesting, but also the most creative part of the civil engineering work. A clever basic idea minimizes the difficulties in both design and construction. Given that it is now possible to calculate and construct anything, it is not very few who come to the wrong point of view that the number of problems being considered ensures design excellence. Apart from the basic idea, however, there are also the details, which are considered to be individual, each compared to the overall result, giving the impression of being insubstantial.

However, the result of the correct handling of a large part of the range of details according to Michael Angelos is not a detail but leads to perfection. Among the details are the selection of cross-sections based on the criterion of economy, when this is compatible with the other design factors and, above all, safety.

However, it should not be overlooked that local economics does not always serve the overall economy of construction due to the complex interaction between structural elements under seismic loading. For example, an increase in cross-sectional dimensions of a wall alleviates generally the remaining members of the system, but by reducing the system's eigenperiod causes an adverse impact on seismic actions, which increase, while possibly aggravating, the earthquake's torsional moments and perhaps the system's regularity.

3. FOUNDATIONS

3.1. General

The most qualitative case of foundation for high-rise buildings made of reinforced concrete is the raft foundation. The reason why this type of foundation is preferred despite the increased consumption of materials, is the speed of manufacture and hence cost reduction by reducing the cost of labor and the non-essential construction of a basement slab. As far as soils of poor quality are concerned, this solution is a must, considering the increased load values resulting to the foundation in high-rise buildings. The high stresses developed in the raft foundation in case of non-dense columns leads to increase in thickness, and therefore the cost. Although a slab of reduced thickness results in large reinforcement ratios, this solution leads to a reduced cost [7-10]. One way of reducing the slab thickness in the case of very sparse columns is the application of prestress. The work herein tests solutions of both reinforced and prestressed concrete of a raft foundation. The reduction of the thickness leads to the manufacture of inverse fungi on the foundation, at the positions of the column loads, to avoid risk of puncture (Fig. 1). The reduction of the thickness leads to the manufacture of inverse drop on the foundation, at the positions of the column loads, to avoid risk of puncture. It is noted that the presence of inverse drop contributes service advantages, while the puncture reinforcement at positions in question also functions as suspension reinforcement.

In order to study the behavior of the foundations, several variants of a ten-storey spatial system were examined. Main parameters of the study were the presence of groundwater, the existence of a 1.0 m width perimetric cantilever to the raft foundation and the thickness of the slab and of the inverse drop. Basic parameter was the size of the spans, namely the density of the column grid.

3.2. Construction description

The construction to be examined is a square plan with a side length of 20.0 m. It consists of a ground floor of 4.5 m high and nine floors of 3.0 m each. The building does not have beams in the superstructure, and its slabs are slabs with drop panels. To shape the width of inverse fungi, it is chosen to extend at a distance of 2h from the side of the column to avoid the risk of puncture. Eight variants of the following column grids were tested: (A) 5.0x5.0, (B) 10.0x5.0, 10.0x10.0 and (C) 20.0x20.0 (Table 1).

Fig. 2 shows case A2 and Fig. 3 displays the plan in case of Γ1.

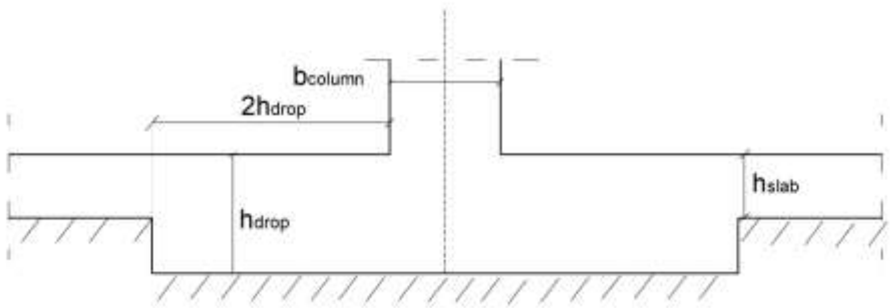

Figure 1. Inverse fungus dimensions in raft foundation. Slabs/fungi thicknesses: (A) 0.40/0.35, (B) 0.40/0.60 and (C) 0.50/1.00

Table 1: Raft foundation cases examined

Case	Spans	h_{slab} (m)	$h_{slab+fungi}$ (m)	Basement	Cantilever
A1	4	0,40	0,75	Yes	Yes
A2	4	0,40	0,75	No	Yes
A3	4	0,20	0,75	Yes	Yes
A4	4	0,20	0,75	No	Yes
A5	4	0,40	0,75	Yes	No
A6	4	0,40	0,75	No	No
A7	4	0,20	0,75	Yes	No
A8	4	0,20	0,75	No	No
B1	2	0,40	1,00	Yes	Yes
B2	2	0,40	1,00	No	Yes
B3	2	0,20	1,00	Yes	Yes
B4	2	0,20	1,00	No	Yes
B5	2	0,40	1,00	Yes	No
B6	2	0,40	1,00	No	No
B7	2	0,20	1,00	Yes	No
B8	2	0,20	1,00	No	No
Γ1	1	0,50	1,00	Yes	Yes
Γ2	1	0,50	1,00	No	Yes
Γ3	1	0,20	1,00	Yes	Yes
Γ4	1	0,20	1,00	No	Yes
Γ5	1	0,50	1,00	Yes	No
Γ6	1	0,50	1,00	No	No
Γ7	1	0,20	1,00	Yes	No
Γ8	1	0,20	1,00	No	No

Figure 2. Case A2

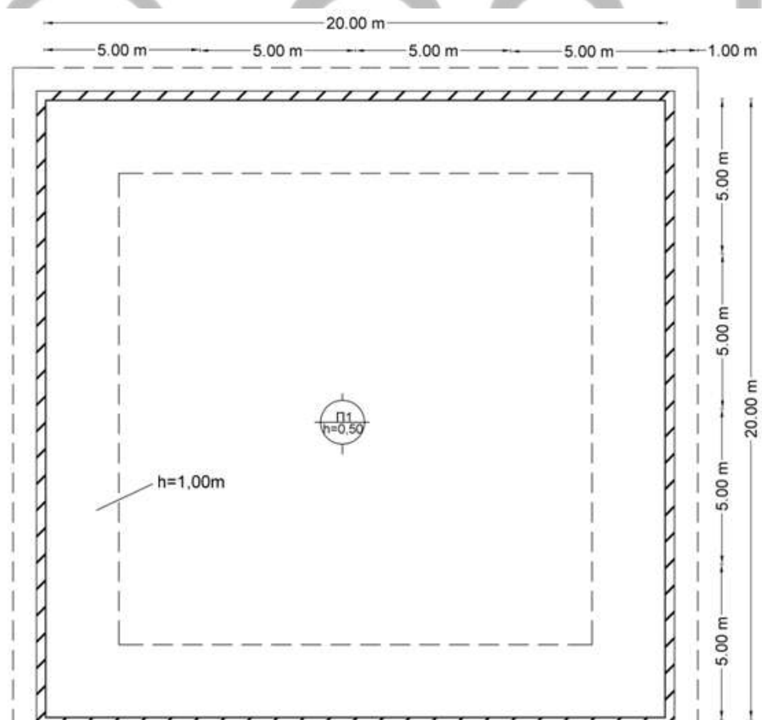

Figure 3. Case Γ1

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3.3. Results

As shown in Fig. 4, the largest demand for reinforcement is clear for the central area of the floor plan of group B, having the required reinforcement increased by 160%. However, the reinforcement ratios remain, even for these positions in group B, at reasonable levels. As the minimum reinforcement ratio at critical puncture positions should be equal to 5‰, in position 3 the reinforcement ratio reach the maximum value of all cases and is in the order of 7‰.

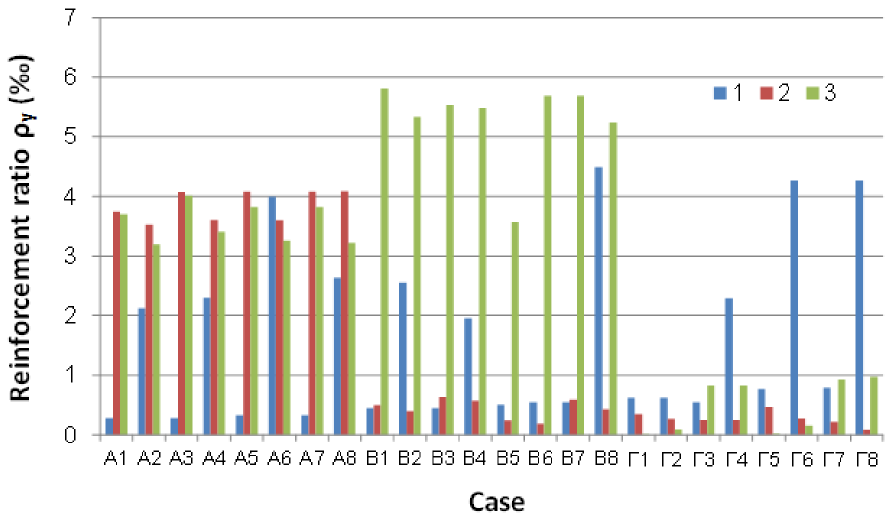

Figure 4. Required reinforcement percentage in raft foundation in characteristic points of y-y direction

3.4. Application of prestress to foundation

In case of Γ6, where the span of the foundation slab is of the order of 20 m, the central area of the span remains inactive, and this is shown by the slab strain in this group of cases under bending. As the end regions are extra burdened compared to the central ones, the way they can be activated is the application of prestress. It has been mentioned in previous cases that pre-tensioning can be a way of transferring intensity from one area of a structural element to another.

Referring to the geometry of the wiring in prestressed slabs of raft foundations, the most realistic approach is achieved through wiring of 4th degree. The present work tested geometry of 2^{nd} and 4^{th} degree (Fig. 5). After a preliminary study, it emerged that tendons were placed with 7 steel ropes each in circular tubes at distances of 25 cm in the support zones and every 50 cm in the span zones. From the check of developed stresses in the foundation slab, for both directions of the slab, for its upper and lower part in characteristic positions, it emerged that the critical tensile stresses can be significantly reduced after stretching the tendons. The objective targeted was the reduction of stress below the tensile stress of the concrete, which is equal to 2 MPa. Even if this is not achieved in some places, the stresses are significantly reduced and thus a more favorable situation in terms of serviceability is achieved.

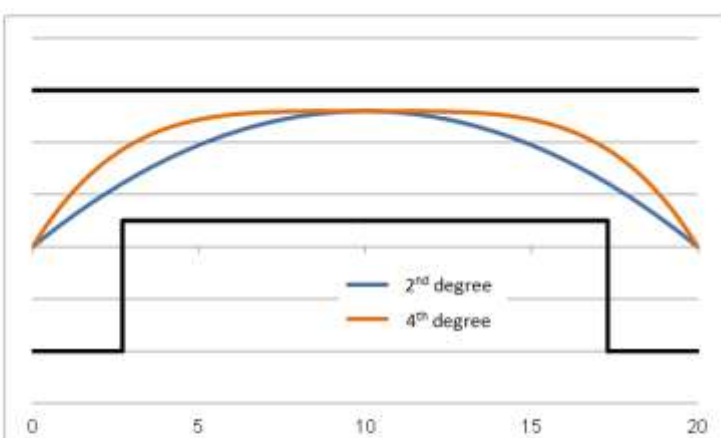

Figure 5. Wire geometries examined

3.5. Analysis of results

From the developed stress diagrams in the foundation, it seems that in the supports with the geometry of 4^{th} degree there is a tensile stress reduction, in many cases below the strength limit. In the span positions, the geometry of 2^{nd} degree in the wiring may cause a contra-load build-up in the center of the span that it may lead to an excess of the tensile stresses (In the bottom flange of the slab at positions 3 and 6 in the x-x direction).

In the framework of the present work, soil pressures on the foundation slab were checked before and after the application of pre-stress for service load (Fig. 6). With pre-tensioning, the central (initially inactive) area of the plan is activated, while the support areas are significantly relieved. The uniformity of stresses is achieved to this extent thanks to the flexibility of the foundation slab.

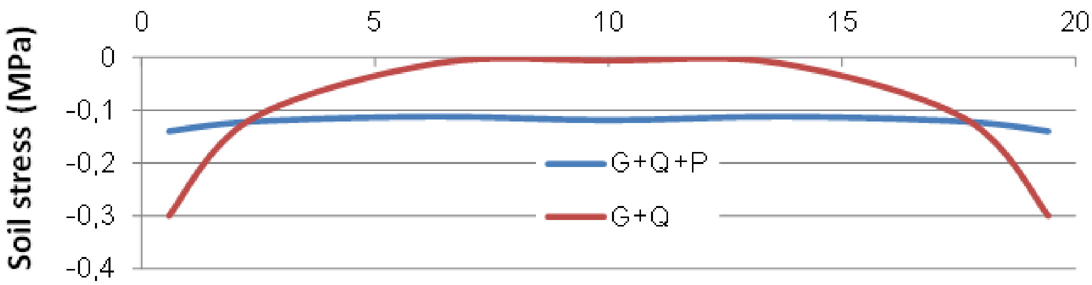

Figure 6. Pressures of the soil before and after application of prestress

3.6. Conclusion

Reducing stress in the slab leads to a reduction of the slab thickness, which in turn leads to lower construction cost as well, since under the current steel price per kilo and concrete price per cubic meter, it is true that with thinner elements, although many reinforcement bars arise, these elements are more economical than those with a large thickness and fewer reinforcement bars.

4. BASEMENTS

4.1. General

In this work, a multi-storey building without beams is considered featuring underground levels or not, in order to examine the contribution or not of the basement in the economics of a building.

4.2. Construction characteristics

The building tested consists of ground floor, eight floors and three cases of foundations. The height of the typical floor is 3.0 m while the height of the ground floor is 6.0 m. The floor area is equal to 460.00 m2. The structure has no beams in the superstructure and thus exploits the advantages offered by this type of construction. The absence of beams requires the addition of walls to the system to deal with the seismic loads developed. On the perimeter of the superstructure, beams having dimensions 0.25x0.70 m are positioned which greatly contribute to the reduction of the seismic movements. The slab thickness is calculated based on the provisions of Eurocode 2 and is equal to 0.24 m, the concrete quality is C25/30 and the steel quality is B500C.

4.3. Variations of the building examined

4.3.1. Building without a basement

The first variant of the construction examined lacks a basement and the thickness of the foundation slab is equal to 1.20 m. Bending check was performed for both 1.35G+1.50Q and seismic combination. It was chosen to place a flexural reinforcement mesh Φ20/200 in both directions, on the upper and lower flange of the slab. Additional reinforcement bars are placed in the support positions, wherein the mesh reinforcement is insufficient. A puncture check is also performed and puncture reinforcement is positioned at the support where a requirement exists.

4.3.2. Building with a basement

The main difference of this solution to the original is the addition of the basement at the building. The thickness of the perimeter wall is equal to 0.30 m and the thickness selected for the raft foundation is 0.60 m. The addition of the basement allows this reduction. The bending reinforcement which is arranged in mesh form across the slab is Ø14/200 with additional reinforcement where necessary. The reason for selecting a dense reinforcement arrangement, even if not required, is that this dense provision favors serviceability. Specifically, it provides a reduction in the crack width, which is important especially when the underground water horizon is at a high level. Also, a puncture check was performed and due to the relatively reduced thickness, it is suggested that the reinforcement spacing should be equal to 2.0d from the side of the vertical elements for security reasons.

4.3.3. Building with two basements

The third variant to be investigated comprises the existence of two basements, each one of which has a height of 3.0 m. The thickness of the foundation slab is 0.60 m and the same bending reinforcement in mesh form was placed like in the case with a basement. Puncture reinforcement requirements are similar to the case with a basement.

4.4. Comparison of results between the three variants

4.4.1. Bending moments at the foundation slab

The work herein shows the comparison of the moments in the foundation slab due to seismic load (combination of G+0.3Q±E), for the cases examined. Along the perimeter of the plan for the cases where there is a basement, the moments developed are essentially smaller compared with the case where there is no basement. At position of internal column, the moments do not vary more than 23% between the cases tested. On the other hand, there is a drastic moment reduction due to the existence of the basement at wall positions. As these are the main structural elements taking seismic shear, their behavior determines the stress transferred to the position of the foundation in the respective positions. Thus, this reduction allows the reduction of the slab thickness to such an extent that the reinforcement ratios developed each time are eligible, even if they are increased. Depending on the case under consideration each time, this solution may prove more economical from an increased slab thickness solution.

4.4.2. Bending moments at the wall bases

The basement ceiling slab can function as a fulcrum, by considerably reducing the moments to the base wall. This feature is discussed in this work by noting the results of the moments at the base of the walls. The results show a significant reduction, which may reach up to 95% of the moment of the 1st case.

4.5. Concrete volume saving

In typical building construction, the criterion that usually characterizes the cost of manufacture is the volume of concrete to be used. In the case of reducing the thickness of the raft slab at half the thickness which would have if there was not a basement, the volume of the concrete below the ground level can be significantly reduced, thus reducing the overall construction cost. This volume reduction is shown in Table 2.

Table 2: Volume of concrete needed for each solution, measured below ground level

Basement level	Concrete volume (m^3)
0	552
1	431
2	585

The construction of a basement proves more economical solution compared to the solution with no basement. The third solution requires 30 m^3 more concrete compared with the conventional solution. Although a small increase in the quantity of material occurs, the advantages of adding a further basement are important as the functionality of the building increases. Such spaces can be used as parking lots, warehouses, or stores.

Conclusion

1. The presence of the basement results to the reduction of bending moments due to seismic loading in the base of the walls located inside the plan view.
2. The reduction of internal forces at the base of the walls results in lower bending moments in raft slab, allowing the reduction of the thickness, thereof leading to savings in construction costs.

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