Optimal Layout for Intermediate Steel Moment Resisting Frames with Special Chevron Braces

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Abstract

Background: Topology and shape of the structures are very important in terms of the building's weight and cost. Regarding structural performance, dual structural systems, consisting of steel moment resisting frames with chevron braces, have many applications worldwide and especially in Iran. **Methods/Statistical analysis:** In this paper, construction cost optimization of dual structural systems is investigated for the different number of floors, span lengths, and soil types. In total, 18 building models are examined and estimated for costs, which are defined in accordance to the architectural requirements for parking areas and code regulations for design. Storey heights are assumed to be 3.5 meters for all models and the construction site is in Tehran, Iran with very high earthquake risks. Construction cost is estimated based on the current Iranian price list. **Findings:** The obtained results are compared to each other, regardless of the land price and then the optimal ratio between the land price and construction costs is calculated for the most favorable model. The findings show that 5-storey structures with shorter span lengths (5.6 meters) are more economical. However, in the case of 10 and 14-storey structural models, 7.5 meters span for parking of three vehicles, is more economical. In the other words, by increasing the height of the building the optimum span length increases. In addition, the type of soil has a remarkable effect in the total structural cost by increasing the height of the structure **Application/Improvements:** The results of this article are very useful for engineers to decide how to locate columns and frame elements in a specific plan in order to achieve an optimal layout.

Keywords: Chevron Braces, Intermediate Moment Resisting Frames, Optimal Layout, Special Braces, Steel Frames

1. Introduction

Placement of the equipment, vehicles, and machines with specific dimensions is important in the structures, such as garages and storage rooms, in terms of construction cost in large quantity. The use of steel sections is of interest to engineers due to their high ductility, architectural considerations, and ease of application from long time ago. Steel structures with chevron braces are used in Iran and other countries because of their ease of construction and acceptable resistance against lateral loads. Although, this system has not a high lateral resistance in many cases, however, engineers utilize chevron bracings to control deflection of the structures.

Structural optimization includes many parameters to be determined such as lateral braced system, location of braces, number of braces, material characteristics, span length and storey height and on the soil type of the building to be constructed. These parameters themselves also affect each other. Therefore, some of the parameters should be assumed and the other parameters to be studied.

Many engineering problems are complex and optimization of these systems requires a huge evaluation, therefore, they could not be solved using mathematical methods or parametric studies. In these cases, optimization algorithms are applied to find the best solutions[1-3]. The effect of yield mechanism selection on the performance based plastic design of steel moment frame is reported in the literature[4]. In other research, five types of braces, including single diagonal, X, chevron, reverse chevron and symmetrical EBF braces, are studied to minimize structural weight[5]. Optimal placement of X-braces in the

short, medium, and high-rise structures for nonlinear seismic response is also proposed in the literature[6].

Furthermore, in a research on optimal seismic design, a frame that is placed in the interior of a three storey building is studied and results reported[7]. The importance of topology (number of columns and their placement) is also investigated and practical optimal topologies for reinforced concrete moment resisting frame structures are proposed[8]. Similar works have been performed for other systems of steel, reinforced concrete and composite structures. According to these studies, optimal layout varies for each system[9-10].

2. Structural Models

In this study, 18 steel structural models are defined with intermediate steel frames and special chevron bracing systems. Three types of plans and bracing locations are defined based on the architectural requirements to provide parking area, as shown in Figure 1. According to this figure, three spans with length of 5.6, 7.5, and 11.2 meters and symmetrical bracing placement are selected. Floors are assumed to be composite slabs. Structures with 5, 10, and 14 stories are considered at a storey height of 3.5m per level. It is assumed that structural models are in a region with very high relative earthquake risk, according to the Iranian codes[11-12]. Specifications of soil types II and III for the structure as well as the earthquake forces are employed according to the Iranian standards[11] and national building codes[12]. Structures are analyzed in accordance with the American standards[13-14]. Uniform equivalent live, dead and partition loads are considered as 7, 2 and 1 KN/m², respectively. Total area for each floor is assumed to be 530 square meters. Type of reinforcement bars and concrete for foundation are specified as AIII (yielding stress of 400 MPa) and C30 (compressive strength of 30 MPa), respectively.
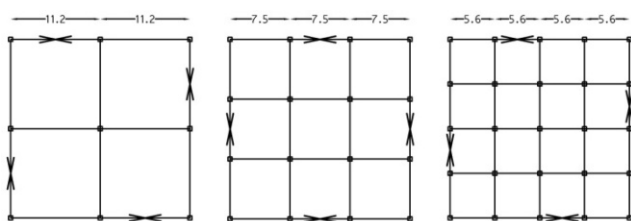

Figure 1. Plan view and bracing placement for the structural models.

3. Analytical Results

3.1 Five-Storey Buildings

Total height of this group of structures is 17.5 meters. Figure 2 shows the required bars for foundation for different spans and different soil types. It is observed that the required foundation bars decreases 63% and 51% for soils type III and II, respectively, as the span increases. This figure also shows that soil type III is more sensitive to the number of columns, and the required bar for foundation increases sharply by increasing the number of columns. Total required steel is shown in Figures 3 and 4 for different soil types, including the required steel for foundation, beams, columns, braces, and connections.
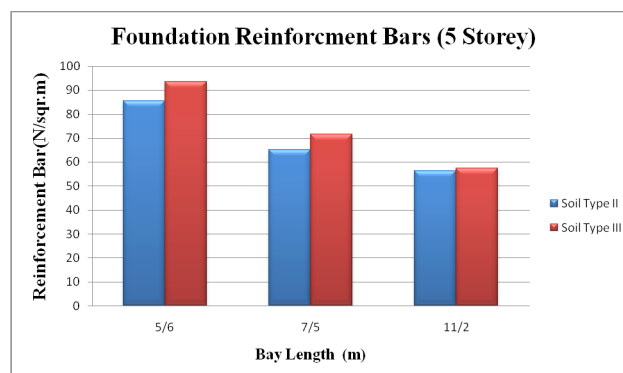
Figure 2. The required bars for foundations of 5-storey structures.
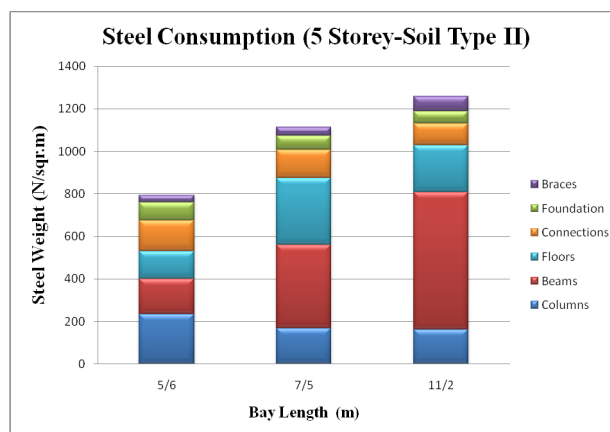
Figure 3. Required steel for 5-storey structures: soil type II.
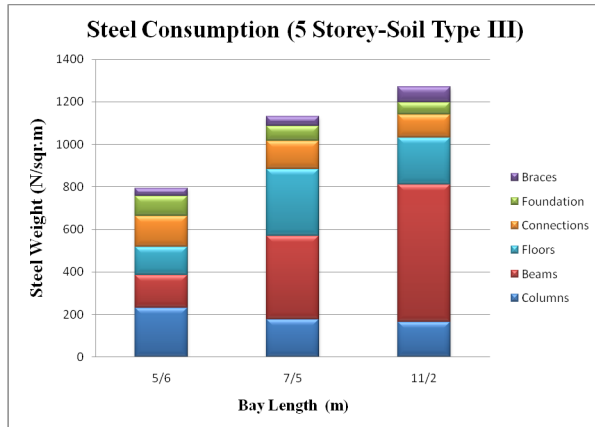
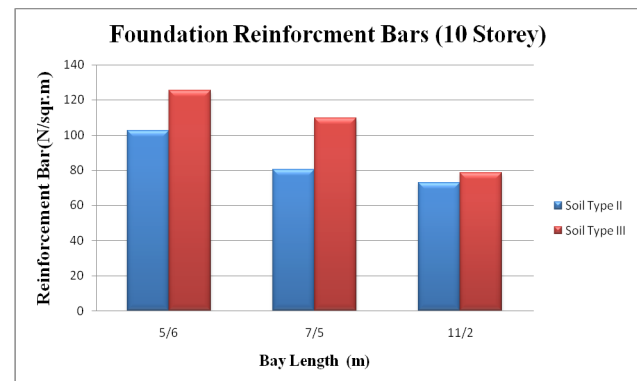**Figure 4.** Required steel for 5-storey structures: soil type III.

According to the above figures, it can be stated that through increasing the span length, the required steel decreases in columns; however, it increases in beams, which is due to the increasing design loads on beams. In the other words, increasing the span length has a large effect on beams. However, the increase in the required steel for beams is greater than the reduction value for columns. In addition, the required steel for connections decreases by increasing span length. This result shows that although longer spans need stronger connections, the required steel for connections decreases because large spans need fewer connections. The required steel for roofs for the 5.6 meter span is the minimum and for the 7.5 meter span it is the maximum, since joists (secondary beams) are used in the 11.2 meter span, which decreases the steel, compared to the 7.5 meter span.

Comparing Figures 3 and 4, soil type does not have a significant effect on the required steel for 5-storey structures, which can be related to the low height of the structure in relation to the effect of the earthquake. Moreover, in this paper, the use of plates and boxes as cross sections for columns and beams caused these structures to be designed slightly stronger than needed. This is due to the construction and code limitations. Required excavation, concrete and total costs are discussed in the next section.
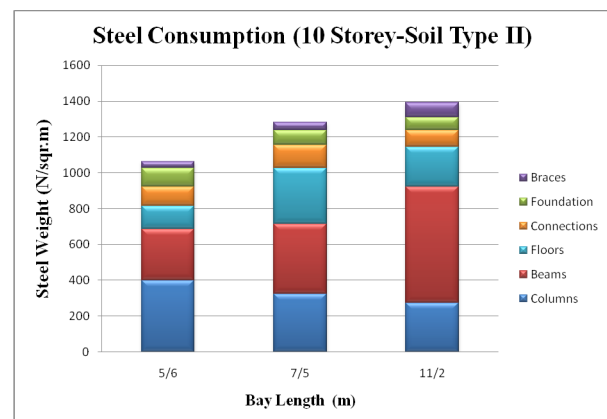
3.2 Ten-Storey Buildings

This group includes building models with the height of 35m. As can be seen in Figure 5, similar to the 5-storey building models, required bars for foundation are decreased

by increasing the span length. This reduction for the soil types II and III is up to 40% and 59%, respectively. Total required steels in details (for foundation, braces, beams, columns, and connections) are also shown in Figures 6 and 7 for different types of soils. According to these figures, it can be seen that the consumption pattern is similar to the 5-storey buildings, which means that by increasing the span length the required steel in columns is reduced, however, it is increased in the beams. In these models, the required steel for joints is reduced and the required steel in braces is increased by increasing span length. By comparing Figures 6 and 7, it is observed that the effect of soil type on ten-storey structures is remarkable and it requires a bigger amount for structures with smaller spans. In the other words, further material is needed (more than 30%) for spans of 5.6 meters for soil type III.

Figure 5. The required bars for foundations in 10-storey structures.

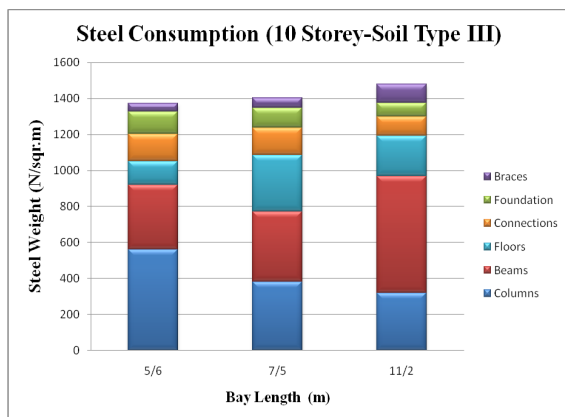**Figure 6.** Required steel for 10-storey structures: soil type II.

Figure 7. Required steel for 10-storey structures: soil type III.

3.3 Fourteen-Storey Buildings

The last group includes structural models with the height of 49 meters. The required steel for foundation is illustrated in Figure 8 for two different soil types and three arrangements for columns. Based on this figure, the required steel, in contrast with 5 and 10-storey building models, is increased by increasing the span length, which shows a change in the pattern for the required steel. In the other words, increasing the height of a certain level and the effect of soil foundation is remarkable for taller buildings.
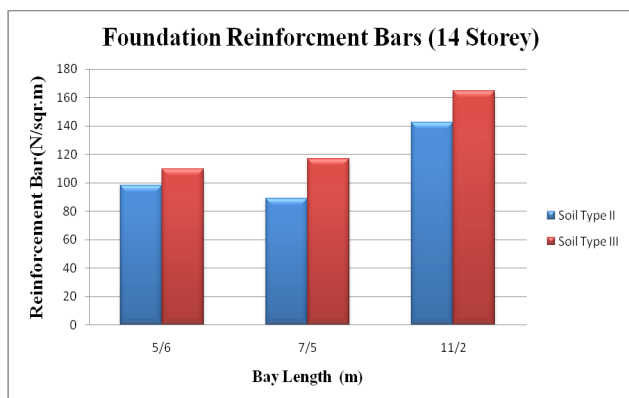

Figure 8. The required bars for foundations in 14-storey structures.

Figures 9 and 10 represent the required steel for the structural elements in soil types II and III, separately. The increase in the required material in relation to the type of soil is evident in all three span types, while in the 10-storey structures the difference is more evident in

structures with shorter spans, and large differences is not seen in the required steel for 5-storey structures.

According to Figures 9 and 10, as well as the previous groups, required amount of steel is reduced in columns with increasing the length of spans, and vice versa, in beams. Finally, the required amount for this increase is more than the reduction in columns, so the amount of required steel is increased in large spans. The required amount of steel in braces as well as in other groups in large spans is increased.

Unlike braces, required steel is decreased in joints by increasing the span length. By comparing this amount for connections, it is observed that the required material for short spans in soil type III is considerably more. This result shows that the required steel for connections is very sensitive to the soil type.
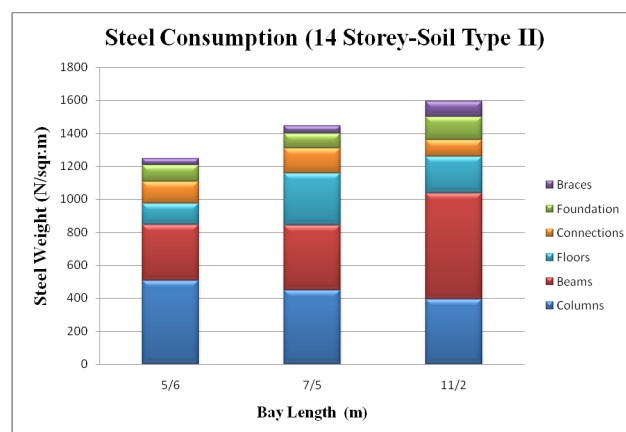

Figure 9. Required steel for 14-storey structures: soil type II.
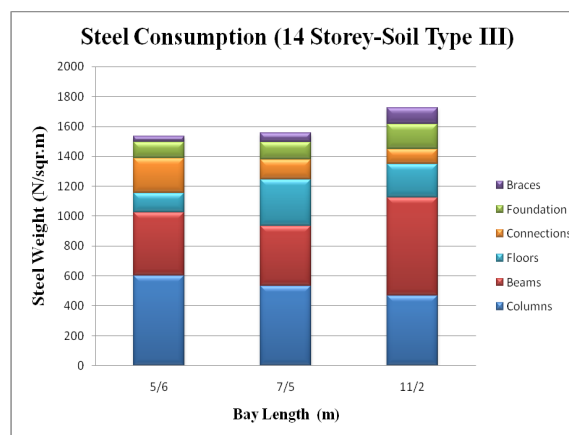

Figure 10. Required steel for 14-storey structures: soil type III.

4. Discussions

In this section, the effect of three basic parameters of span length, soil type, and structure height on the construction cost is investigated. Given that the foundation dimensions for both soil types are considered to be similar and only the required bars are obtained and are different, therefore the required excavation is equal in both soil types. According to Figure 11, the volume of the required excavation per square meter for the models shows that this amount is reduced by increasing the height in structures with 5.6 meters span. However, it is observed that 10-storey structures with the span of 7.5 meters or 11.2 meters require optimal excavation, because of the mat foundations.

In Figure 12, the total required concrete and steel per square meter are shown for all structures and different soil types. In 14-storey structures, the required concrete volumes remain plateau due to the same mat foundation for all spans. However, it is reduced in 5 and 10-storey structures by increasing the span length, because the number of columns is reduced. In general, the most amount of concrete is required for 5-storey structures with a span of 5.6 meters.
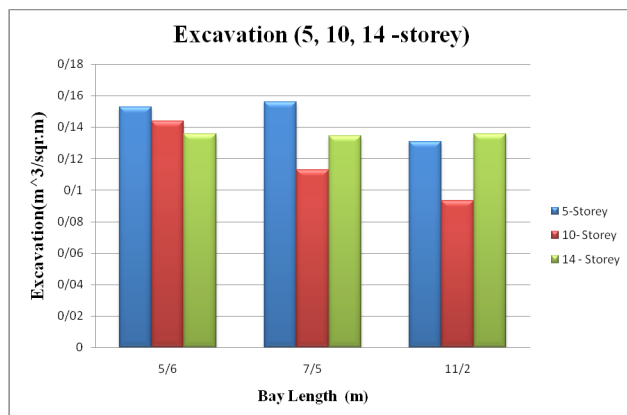

Figure 11. Required excavation for structural models.

Figure 13 shows the required amount of steel for all models. This amount increases with increasing the span length and the height of the building, and it depends on the soil type. In fact, the rate of increasing for the required steel is greater in soil type III compared to soil type II.
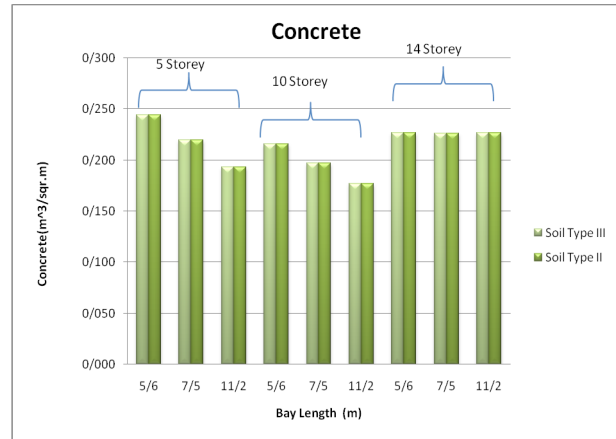

Figure 12. Required concrete for all structural models.
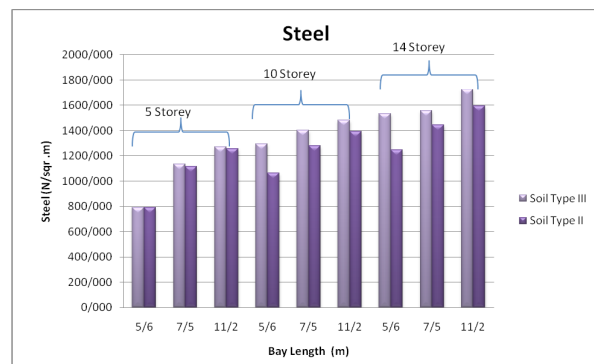

Figure 13. Required steel for all structural models.
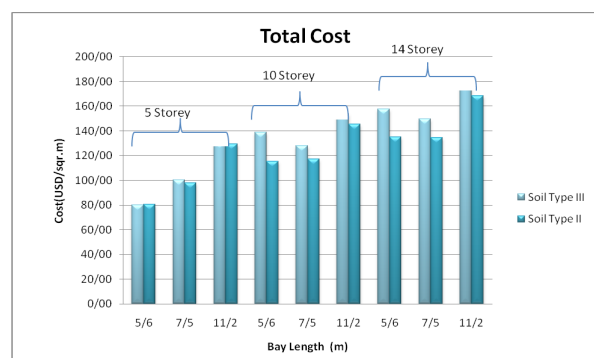

Figure 14. Estimated construction cost per square meter for all structural models.

Figure 14 shows the total estimated construction cost per square meter for all structures. An overview of all outcomes indicates that the construction cost shows

a steady increase for high-rise structures. However, the estimated cost of structures in each group with a larger span is near to those of the next group with small and medium spans of the next group. From the diagrams, it is clear that increasing the span length causes an increase in the cost for 5-storey building models, but in the next two groups, the minimum cost is for 7.5 meter span, which indicates that when the height increases the smallest span is no longer economical.

Although a limited number of building models are investigated, adequate information is available to apply mathematical evaluations to obtain a correlation between costs and parameters, (number of stories and span length) providing an overall representation of how these parameters are related to the costs. In Table 1, the correlation between the costs and span lengths are calculated for structures with 5, 10, and 14 story numbers, separately. According to this table, the relationship between the cost and the length of the spans in the 5-storey structures only, is 1.000. This illustrates a very direct relationship between these parameters. In the other words, the effect of the other parameters is negligible. According to Table 2, it is also observed that the relationship between cost and number of stories in

structures with a span of 7.5 meters is 1.000 and it shows that in this span the effect of the number of stories is dominant with respect to the effects of other parameters.

Table 1. Correlation of cost and span length

SOIL TYPE		II	III
STOREY NUM.	5	1.000	0.998
	10	0.959	0.728
	14	0.940	0.847

Table 2. Correlation of cost and number of stories

SOIL TYPE		II	III
SPAN LENGTH	5.6	0.995	0.975
	7.5	0.999	1.00
	11.2	0.984	0.992

Land price is employed as a coefficient of the final cost per square meter. Comparing construction costs of the structures, an optimum ratio is selected for land price to make economic selection between the two models. The calculated coefficients are shown in Table 3. Using this table, one can compare the two types of structure.

Table 3. Calculated coefficients for the optimal model by considering the price of land as a factor of construction cost

				Soil Type II									Soil Type III								
Cost Ranking				2	3	8	5	6	13	11	10	17	1	4	9	12	7	15	16	14	18
Bay Length				5.6	7.5	11	5.6	7.5	11	5.6	7.5	11	5.6	7.5	11	5.6	7.5	11	5.6	7.5	11
			Storey-N	5	5	5	10	10	10	14	14	14	5	5	5	10	10	10	14	14	14
			Model	6bA2	6bB2	6bC2	6bD2	6bE2	6bF2	6bG2	6bH2	6bI2	6bJ3	6bK3	6bL3	6bM3	6bN3	6bO3	6bP3	6bQ3	6bR3
2	5.6	5	6bA2				3	3.1	4.5	3.2	3.1	4.1				4.2	3.7	4.8	3.8	3.6	4.4
3	7.5	5	6bB2				1.5	1.6	3.3	2.1	2.1	3.3				2.9	2.4	3.6	2.9	2.7	3.6
8	11	5	6bC2				1.2	1.1	1.1	0.3	0.3	1.8				0.7	0.1	1.6	1.4	1	2.3
5	5.6	10	6bD2	4.4	1.8	1.1				5.1	5	11	4.5	1.5	1.2				9.3	8	13
6	7.5	10	6bE2	4.6	2					4.6	4.6	11	4.7	1.7					9	7.6	13
13	11	10	6bF2	8.1	4.8	1.2				2.9	2.7	4.8	8.2	4.5	1.1				2.7	1.1	7.3
11	5.6	14	6bG2	5.3	3	0.3	6	5.4	2.4				5.4	2.7	0.3	0.9	1.9	4.3			
10	7.5	14	6bH2	5.3	2.9	0.3	5.9	5.3	2.5				5.4	2.7	0.3	1	1.8	4.4			
17	11	14	6bI2	8.5	5.6	2.3	16	15	5.6				8.7	5.3	2.3	7.5	11	3.3			
1	5.6	5	6bJ3				3.1	3.2	4.5	3.2	3.2	4.1				4.2	3.8	4.8	3.8	3.6	4.4
4	7.5	5	6bK3				1.3	1.5	3.1	2	2	3.2				2.8	2.2	3.5	2.8	2.6	3.5
9	11	5	6bL3				1.1	1.1	1	0.3	0.2	1.8				0.6	0.2	1.5	1.3	1	2.2
12	5.6	10	6bM3	7.3	4.2	0.7				0.9	1	6.2	7.4	3.8	0.6				4.2	2.6	8.5
7	7.5	10	6bN3	6	3.1	0.1				1.8	1.7	8.4	6.1	2.8	0.2				6.5	5.1	11
15	11	10	6bO3	9.2	5.7	1.9				4.9	5	3	9.3	5.4	1.8				0.8	1	5.6
16	5.6	14	6bP3	7.5	4.7	1.7	13	12	3				7.6	4.5	1.6	4.8	8	0.8			
14	7.5	14	6bQ3	6.7	4.1	1.2	10	9.7	1.1				6.8	3.9	1.1	2.8	5.9	1			
18	11	14	6bR3	10	6.8	3.2	21	20	9.2				10	6.5	3.1	11	15	6.6			

5. Conclusion

In this article, building models with different arrangement of columns, heights, and soil types are examined. Models are defined in accordance with specific architectural requirements. Based on the results obtained, by comparing 18 structural models, the following results are achieved.

- Generally, increasing the height and span length lead to an increase in the construction cost, however, in medium and high structures, smaller spans are not necessarily economic.
- Comparing the soil types shows that this factor has a considerable effect in taller structures. In addition, there is a drop in the construction cost-height curve with respect to structures with short spans. Cost comparison indicates that the most important factor of cost is the required steel. This factor is reduced in columns by increasing the span length, however, it is increased in beams, while the total required steel is increased. Long spans require large amount of steel for braces, but it is reduced for connections because there are a small number of joints in these models.
- The required volume of concrete is reduced for larger spans. This is since the number of columns is decreased in these structures, although in 14-storey structures, this value remains constant due to designing of mat foundations. Correspondingly, the required amount of concrete volume for the foundation excavation is decreased due to the increasing of the length; and 14-storey structures are an exception to this due to the presence of the mat foundation.
- Considering the price of land as a proportion of the price of construction, optimal ratios can be determined. In this case, tall buildings with high construction cost may be justified economically.

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