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# Optimal Topology Design of Intermediate Steel Moment Resisting Frames with Reinforced Concrete Shear Walls

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## Abstract

Optimization of structures is in the form of optimizing the weight of building and it consequents in costs reductions, while retrofitting against earthquakes is an inevitable issue that may provides high level of ductility level for structures. One of the building systems that have a suitable resistance against lateral loads, especially earthquake loads, is the dual system of steel moment resisting frames with reinforced concrete shear walls. In this study, a number of building models of steel frames with reinforced concrete shear walls with intermediate ductility level, with different spans and storey numbers were modeled to obtain the best cross sections for beams, columns, and shear walls. Three types of spans satisfying architectural requirements of parking were selected for models and storey numbers are considered to be from 5 to 14, so that static analysis can be implemented. Results indicated that for optimal weight design when the storey number increases the distance of columns increases.

**Keywords:** Optimization, Steel Frames, Intermediate Ductility Level, Moment Resisting Frames, Shear Wall, Weight.

## Introduction

Codes and standards have determined permitted heights for different structural systems, which cannot be exceeded. In these standard, maximum permitted height for intermediate steel moment frame structure is 50 m. To prevent earthquake effects on steel moment frames, such as P-Δ effects, reinforced concrete (RC) shear walls can be used. This system results in a significantly higher resistance for structures compared to other methods. Among the lateral stiffness, RC shear wall provides a resistant system against earthquakes in buildings that have big spans.

In recent years, numerous studies have been undertaken for the optimum use of steel and concrete specifications. A research team consisted of American and Japanese experts have done various studies on composite structures since 1993, and have achieved significant results [1]. Experiments indicate that in steel frame composite systems with concrete shear walls, open small cracks are resulted from quakes. Such cracks after medium earthquakes are repairable with reasonable costs. Another advantage of composite systems is their convenience of implementation, since border beam and column can be used as holders and frame for reinforced concrete shear walls.

In case of intermediate steel frame, however, it should be noted that these frames are designed in a way that after the breakdown of shear wall as a results of inflicted lateral forces, they are resistant towards these forces. According to studies by Peng and Qiang, about 80 to 100 percent of lateral forces to buildings are tolerated by shear walls, while about the same percentage of breakdown force is tolerated by steel frames [2]. Hence as previously stated, it should be noted that steel frames have also critical roles in resisting against lateral forces inflicted to buildings. Some other studies have targeted seismic design and optimization of steel structures [2-8].

Using concrete shear walls in steel structures increases the flexibility of these structures. Babaei (2015) [9] studied the effect of ductility levels of ordinary, intermediate, and special onto the total cost of the RC moment resisting frames [9].

Practical optimal topology for RC moment resisting frames studied by Babaei [10] and interesting results reported for these structural systems. Similar studies for other structural systems have been performed in the literature [11-19].

The main purpose of this article is to explore and obtain optimal topology and arrangements for dual system of steel moment resisting frames and RC shear walls with intermediate ductility level. Structural models are considered to satisfy architectural requirements and building models are similar to those studied in the literature [11-19]. Building models analyzed and designed according to the international [20] and national [21-22] codes.

## RC shear walls

In structural engineering, shear walls are walls made of shear components, with the task of suppressing the effect of lateral loads on the structure. Shear walls are designed to resist lateral loads such as wind and earthquake. Shear walls greatly increase the stiffness, resistance and ductility of the structure, and improves the behavior of structure against quakes. Concrete shear walls include two meshes of vertical and horizontal bars that are continuously interweaved to resist consistently the lateral forces which induce axial, moment, and shear forces.

Shear walls have high inter-sheet stiffness, and causes the lateral stability to increase against shear and moment from quakes. The functionality of shear wall is only moment and axial resistance, but when used in composite structures as brace, it is utilized to resist shear force resulted from quakes.

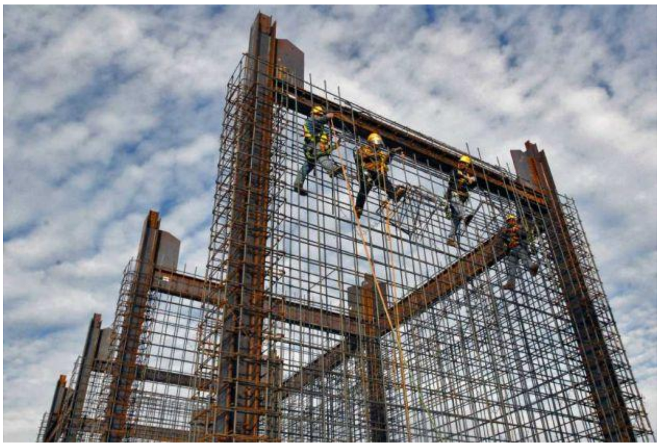


**Fig.1. The implementation of shear walls in steel structures**

Using shear walls in steel buildings instead of steel bracing has some advantages, including the case not having enough control on fitting welds, where utilizing shear wall seems to be a more reasonable approach. Also, cross-bracing, often referred as the most functional bracing system, has complicated behavior, especially during strong earthquakes, and estimating its behavior depends on end condition of bracing, buckling of pressure components, and other phenomena such as local buckling, torsional buckling, fatigue, which can be studied in loading cycles under axial and bending forces. In past quakes buildings with shear walls have shown good performance, which increases reliability for their behavior.

### *A. Steel columns in shear walls*

Steel columns could be used in shear walls in the following two ways:

#### *i. Steel column filled with concrete*

In this method, columns are executed out of shear walls and become connected by shear elements to the shear walls. In this case, columns are designed to withstand flexural and axial forces and concrete walls are designed to bear shear force. For appropriate transfer of forces between steel columns and concrete wall, the column should be considered large which is non-economic. In addition, this leads to designing of big base plates under column which has a strong influence on the design of the foundations. Figures (2) shows a detail for composite shear walls with steel hollow columns.

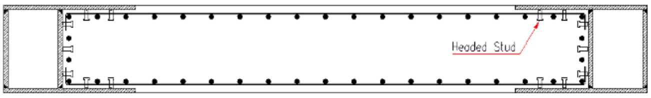


**Fig.2. Details of composite shear walls**

#### *ii. Steel column encased in concrete*

In this method, steel columns are encased in the shear walls. In this case, the steel columns in the shear walls act like reinforcement bars. Columns inside shear walls typically can have larger dimensions. Sometimes boundary elements are required in shear walls and these columns can bear the axial forces of equivalent couple form bending moment forces. Figures (3) shows a detail for this kind.

To design shear walls, there is an issue to tend to, steel moment frame should bear 25% of earthquake force without the existence of shear wall. Hence, designing columns on shear walls makes moment frames to function after the breakdown of concrete wall.

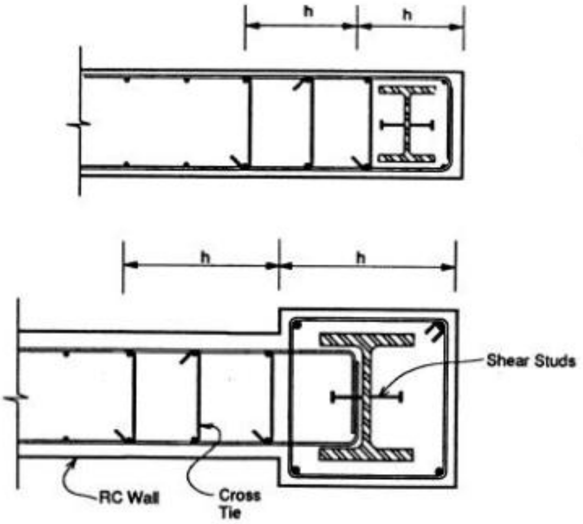


**Fig.3. Details of composite shear walls: end connection**

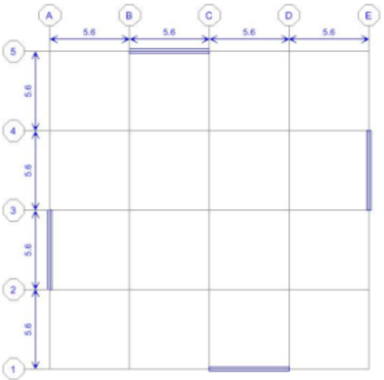
## Methodology

In this study, a number of buildings with different height and spans are modeled by ETABS. These building models are taken as similar to those in the literature [11-19]. Earthquake loads are calculated manually and then defined to the software. All cross sections of beams and columns are defined of steel plates. After modeling, analyzing and designing the elements, they were optimized using heuristic, and the output of the software was imported to SAFE to design foundation, as well as cost estimation of the required materials were implemented. Then, the results were compared and discussed.

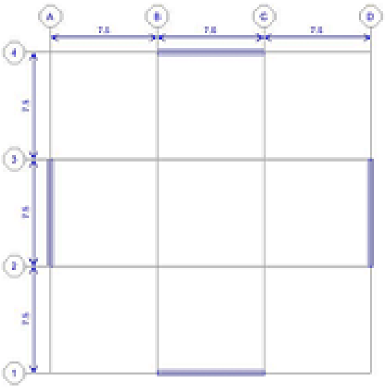
### *A. Definition of models*

To obtain optimum section in buildings with different heights in this project, three types of buildings with three spans of 5.6 m, 7.5m, and 11.2 meters were used (figure 4). These buildings are modeled in three heights of 17.5, 35 and 49 meters, so that static linear analysis can be performed. The lateral load bearing system is intermediate moment resisting frames with RC shear walls. The seismic zone is in the very intense area, according to the Iranian standards [21-22].

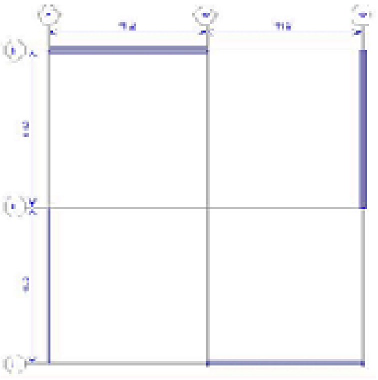
Every building has four shear walls (two walls in each direction). The roof systems are composite, made of steel joists and reinforced concrete slab of 8cm. Columns are in the shape of BOX and all beams are selected as I-shaped compact sections.



**(A) 5.6 m Bays**



**(B) 7.5 m Bays**



**(C) 11.2 m Bays**

**Fig.4. Plan of the models and arrangements of the shear walls**

### *B. Assumptions*

In this study, it is supposed that all structures under study are located in Tehran. These structure are modeled in two types of soils: type II and type III. According to the Iranian standards [21-22]. The weight of partitions are taken to account as floors loads, except for the roof. The loads of quakes are calculated manually and added to the software. The compressive strength of concrete of shear walls are considered to be 300kg/cm$^2$, and all reinforcements are considered to be AIII type, with 4000 kg/cm$^2$ yield strength. In buildings with 11.2 spans, auxiliary beams in the middle of each span on horizontal direction, and two auxiliary beams on vertical spans are deployed. For cost estimation, national cost list for the previous year (2014) were used.

### *C. Distribution of lateral loads in the height of models*

Earthquake loads was calculated manually and using the formula of earthquake force distribution in height, according to the national seismic standard [22]. These forces are calculated based on the soil type. These forces are compared in respect to floor in charts as shown in the following figures.
As can be seen in the figures 5-7, in every building, lateral forces in soil type III is about 1.2 to 1.4 times of the lateral forces in soil type II.

### Size optimization of the elements

After defining the lateral forces to the software, building models are initiated and analyzed. Beams and columns are selected from the lowest possible sections. In the other words, optimization of sections carried out based on experience and heuristic, then shear walls designed. In this procedure, beams on the walls were also designed. However, considering them as non-bearing elements and the bending displacement as insignificant, smaller sections were obtained for them. As expected, lower-level floors needed bigger sections compared to higher-level floors. In addition, the size and extent of used bas in them also varies based on the floor.

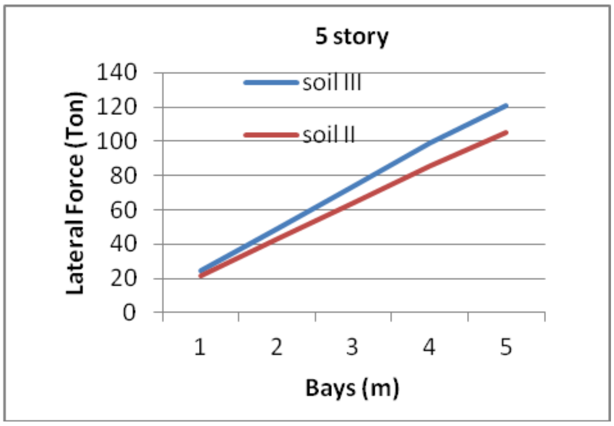


**Fig.5. Lateral force distribution for 5-story models**

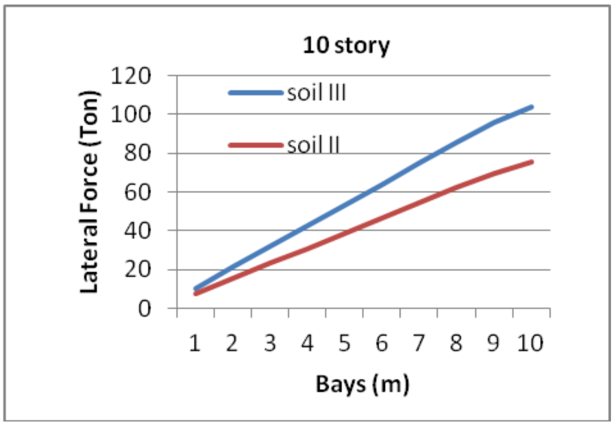


**Fig.6. Lateral force distribution for 10-story models**

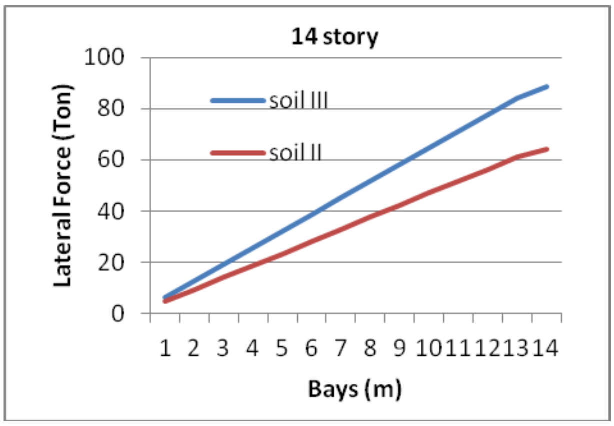


**Fig.7. Lateral force distribution for 14-story models**

After designing process with ETABS software, separate outputs were considered for SAFE and Sazeh Negar (drawing software) to extract the design of foundation and practical plans. Designing of foundation was then performed using SAFE. Only in one case of 14-floor buildings with 11.2 m span which was designed on soil type III, wide foundation was obtained. In addition, practical plans including metering the required materials and volume of them were obtained using Sazeh Negar and Sazeh 90. After that, the cost estimation of building models was undertaken.

## Numerical results and discussion

After obtaining the volume of the require materials for all models and their costs, comparisons between the results were done on soil types II and III. Considering that the applied lateral forces to the models of soil type III were more than those of soil type II, the difference was accounted. Results obtained from the volume of required steel and concrete in models were compared in terms of floor numbers and span length, and were discussed separately in diagrams. In the end, the cost estimation of all models were compared to each other.

### *A. Comparing the required steel and concrete*

The volume of the required steel for columns and beams and the volume of concrete in foundation and shear walls were obtained and are shown in the following figures. The lateral force of building models with 5 floor on soil type III had 15 percent more magnitude compared to the similar buildings models on soil type II. This increase was 37% for models with 10 and 14 floors.

Results indicate that the required volume of concrete on soil type III had increase compared to soil type II. It was also observed that with the increase of spans in models with same heights, the required volume of concrete increased which was due to the increase of shear wall length. However, the increase in shear wall length has made more lateral forces be absorbed by shear wall, and hence less force is applied to steel frames.

The increase of required concrete volume was higher in 11.2m models, as this increase in span is accompanied with increase in wall length. Meanwhile, compared to the required concrete volume in models of soil type III with similar soil type II, models with 5 and 10 floors, there was a 19% percent increase, and in 14-floor models this increase was 21%. Results obtained from the diagram of the required steel indicate that models have required more steel in soil type II than those on soil type III. However, in case of models with 11.2m span, it is different, and required steel amount is higher in soil type III than soil type II. This is due to increase of beams and also the existence of auxiliary beams.

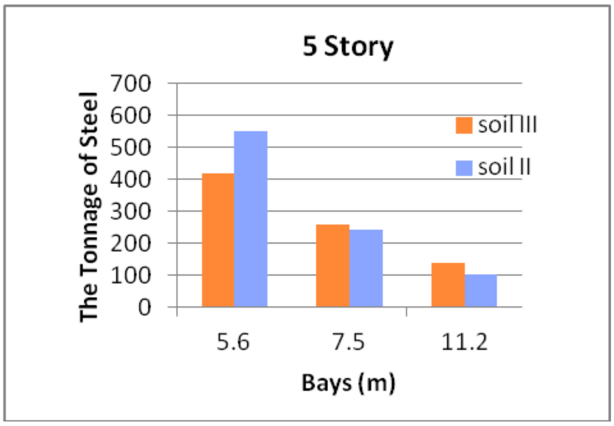


**Fig.8. Required steel for 5-story models**

The amount of required steel decreases as the span length increases, and this decrease in 10-floor models is more than that of other buildings. For example, as span increase in 10-floor building, the amount of required steel decreases about 70 percent, but in 5-floor models, this value is about 30 percent. Figures 8 to 13 demonstrate the amount of required steel and concrete.

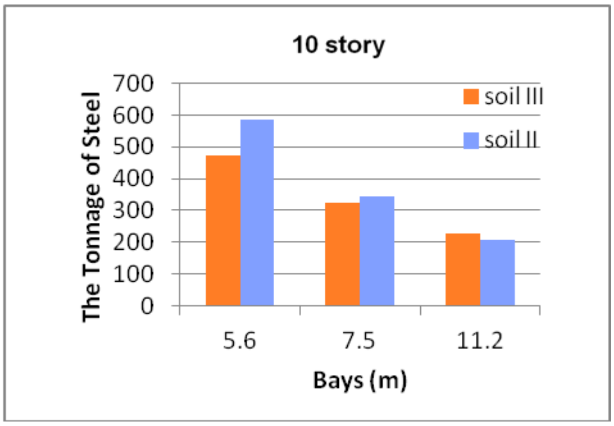


**Fig.9. Required steel for 10-story models**

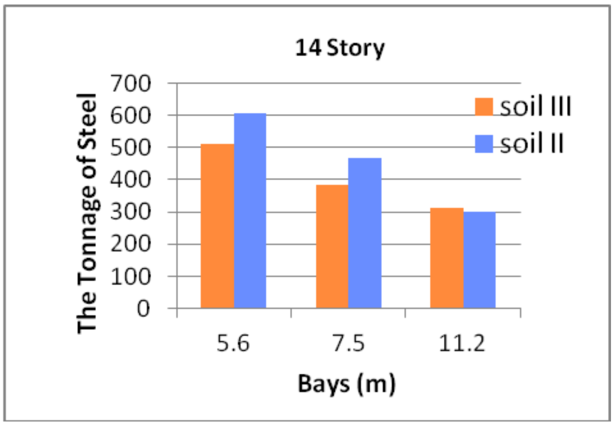


**Fig.10. Required steel for 14-story models**

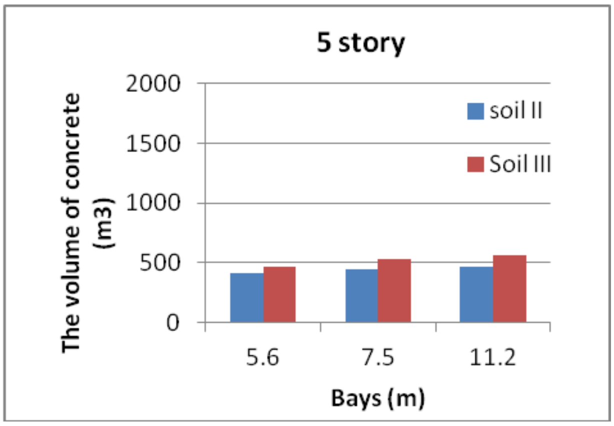


**Fig.11. The required concrete volume for 5-story model**

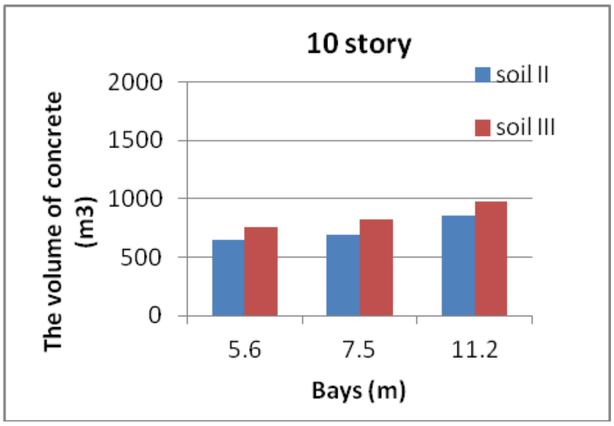


**Fig.12. The required concrete volume for 10-story model**

**TABLE.1. Characteristics of Walls Used in Buildings with Span of 5.6 meters**

| Model | soil type | story | Reinforcement | Width | Length | Weight | Volume of Concrete |
|---|---|---|---|---|---|---|---|
| 14 floors | soil III | 1،14 | Φ28@5cm | 110 | 5.6 | 113128 | 1207 |
| 10 floors | | 8،10 | Φ16@30cm | 30 | 5.6 | 21236 | 400 |
| | | 1،7 | Φ20@15cm | 60 | 5.6 | | |
| 5 floors | | 4،5 | Φ12@35cm | 25 | 5.6 | 11565 | 180 |
| | | 1،3 | Φ20@15cm | 60 | 5.6 | | |
| 14 floors | soil II | 11،14 | Φ16@12cm | 55 | 5.6 | 66546 | 760 |
| | | 7،10 | Φ20@15cm | 65 | 5.6 | | |
| | | 5،6 | Φ25@12cm | 70 | 5.6 | | |
| | | 1،4 | Φ28@8cm | 90 | 5.6 | | |
| 10 floors | | 9،10 | Φ16@30cm | 35 | 5.6 | 20190 | 399.8 |
| | | 5،8 | Φ16@20cm | 50 | 5.6 | | |
| | | 1،4 | Φ20@15cm | 60 | 5.6 | | |
| 5 floors | | 4،5 | Φ14@30cm | 25 | 5.6 | 3856 | 117.6 |
| | | 1،3 | Φ16@20cm | 35 | 5.6 | | |

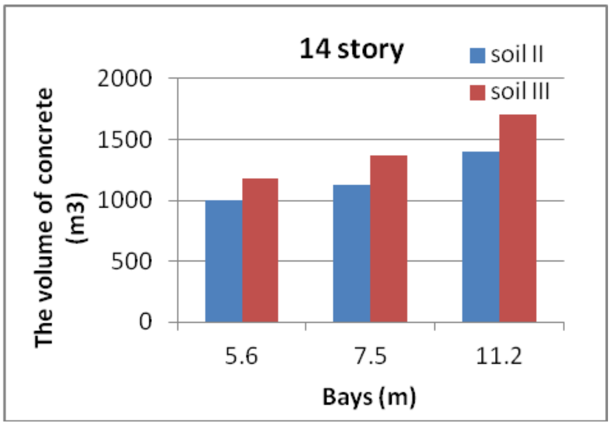


**Fig.13. The required concrete volume for 14-story models**

### *B. Comparing shear wall sizes and their effect on the required steel*

As can be seen in the above figures for required steel, except for the buildings with 11.2 m spans, the amount of required steel in buildings modeled on soil type III is less than those on soil type II. The reason for this is that shear walls tolerate a huge share of lateral forces applied to the structures. In these buildings, large dimensions are obtained for shear walls compared to structures designed on soil type II.

As previously stated, howecer, in models with 11.2m spans, due to the existence of auxiliary beams, and the increase of length of beam in those structures, the amount of required steel has not decreased.Table (1) demonstrate a sample of shear wall designed for 5.6m span model with different floor numbers. It can be seen that dimensions of walls in soil type III buildings and the volume of required concrete is greater than that of buildings on soil type II. According to the figures 11-13 for the required steel and table 1, which lists the specifications, it can be concluded that 60 percent increase of shear wall volume and their reinforcement weights reduces 19% for the required steel weight.

By calculating the increased costs of the construction of these walls, and also the decreases costs of preparing and installing the required steel for these beams and columns, it is concluded that about 16% of construction cost is reduced, while the lateral forces applied to the buildings are approximately increased 30%.

### *C. Comparing structural weight*

Structural weight generally include the weight of the required steel and concrete, and the comparisons are shown in figures 14 to 16. From these graphs, it can be seen that the total structural weight increases by increasing the span length. But the steep of increase for 7.5m to 11.2m, is less than that of 5.6m to 7.5m. On the other hand, as height of the building increases, the difference of weights among structure decreases, meaning that the span length in high-rise structures is less significant.

### *D. Comparing the total structural cost*

The costs of these buildings include excavation, forming of foundation and roof, required steel, and the volume of required concrete. These costs were estimated separately and the results are shown in figures 17 to 19.

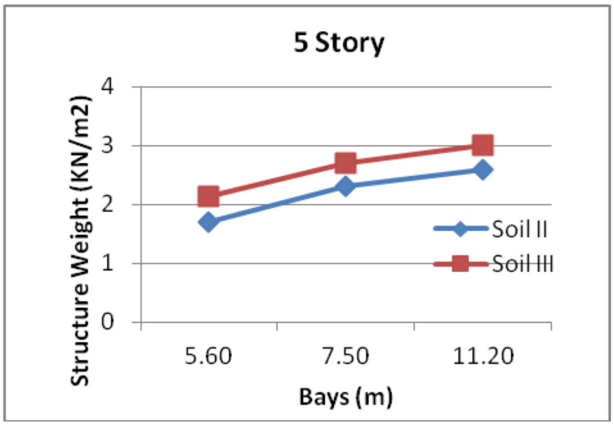


**Fig.14. Total structural weight per square meter for 5-story models**

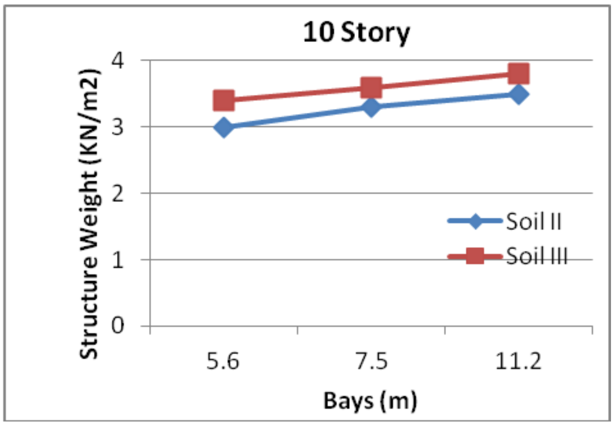


**Fig.15. Total structural weight per square meter for 10-story models**

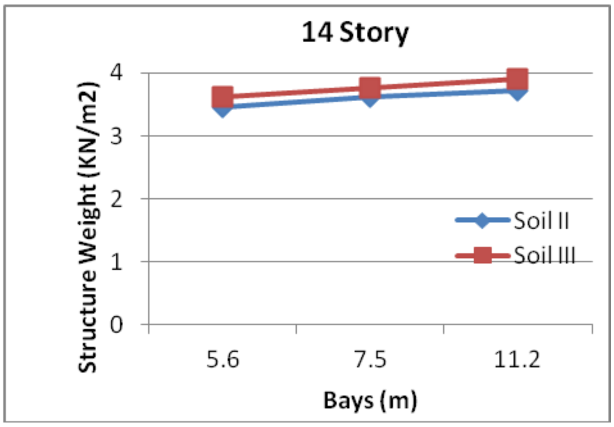


**Fig.16. Total structural weight per square meter for 14-story models**

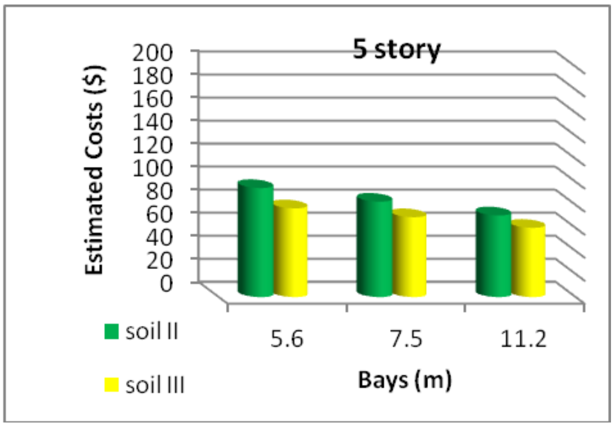


**Fig.17. Total structural cost per square meters for 5-story models**

As shown in the figures, by increasing the span length, the total cost reduces, but more analyses that are precise showed that cost reduction for a 7.5m span is more than that for 11.2m span. For example in 5-floor models, the reduction of costs from 5.6m span to 7.5m span is 12%. The reduction in proportion to the length of span is expected 35% decrease for

11.2 span, but it is in fact 23%. In 10-floor and 14-floor models, the same issue is obtained.

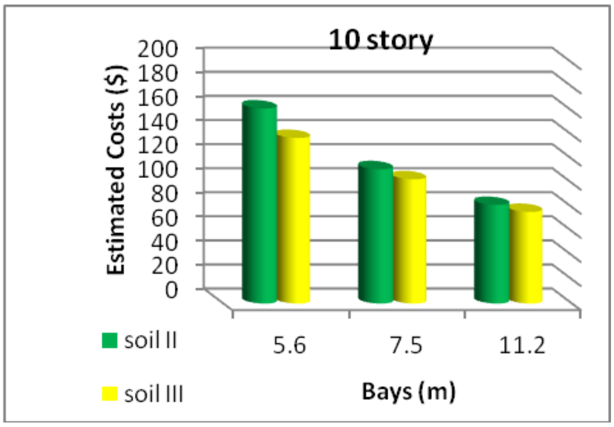


**Fig.18. Total structural cost per square meters for 10-story models**

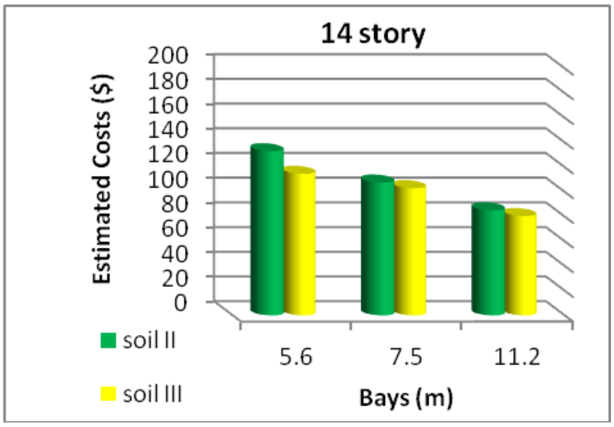


**Fig.19. Total structural cost per square meters for 14-story models**

## Concluding remarks

1. For buildings made of steel moment frames, the best bracing system is reinforced concrete walls, since they have more resistance, fewer costs and high lateral stiffness.
2. Large spans are more economical for buildings made of steel moment frames with concrete shear walls, as using such spans can results in 12% to 20% percent reduction of costs.
3. For steel structures with concrete shear walls as bracing system, it is better to use metal beams on concrete walls. In addition to provide large lateral stiffness, makes the design optimum, as these steel beams can have smaller sections due to small lateral forces.
4. In steel structures with concrete shear walls as bracing system, walls can absorb large lateral force, which decreases steel consumption in moment frames by increasing the diameter of shear wall. This is economic for taller buildings. So, increasing the diameter of shear walls is recommended, which is not only acceptable but also desirable for architectures.
5. Findings indicate that in tall models, the increase of span has more effect on the optimization compared to structures with lower floor numbers. Therefore, it can be said that, considering practical requirements, bigger spans are better from economic point of view compared to shorter buildings.
6. In structures of tall steel moment resisting frame systems, utilizing shear walls provides optimum required material in terms of structural weight.

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