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Construction cost of tunnel form buildings

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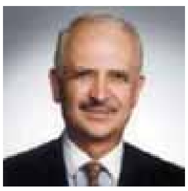

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Professional paper

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A residential building with a lateral load resisting system, adopted as a reference example, is considered in the paper. The system is made of shear walls realized using the tunnel form technology. The building is modelled for a varying number of floors, and the model is also used to consider the applicability of the technology with regard to construction costs. The influence of the type of soil on construction costs is also considered. The results obtain show that mistakes made in determining the soil class may lead to inadequate decisions during selection of the most favourable number of floors, and in the design of structural elements and foundations of buildings.

Key words:
construction costs, number of floors, tunnel form technology, shear wall system, type of soil

Stručni rad

Zeynep Yeşim İlerisoy, Mehmet Emin Tuna

Troškovi izgradnje zgrada pomoću tunelske oplate

U radu se kao referentni primjer razmatra stambena zgrada opremljena sustavom otpornim na bočna opterećenja. Sustav je sastavljen od posmičnih zidova izvedenih primjenom tehnologije bazirane na korištenju tunelske oplate. Zgrada je modelirana za razni broj katova, a pomoću modela razmatrana je prihvatljivost tehnologije s obzirom na troškove građenja. Razmatran je u i utjecaj vrste tla na troškove građenja. Dobiveni rezultati ukazuju da greške u određivanju kategorije tla mogu dovesti do krivih odluka pri odabiru najpogodnijeg broja katova, te pri projektiranju konstruktivnih elemenata i temelja građevina.

Ključne riječi:
troškovi građenja, broj katova, tehnologija tunelske oplate, sustav posmičnih zidova, vrsta tla

Fachbericht

Zeynep Yeşim İlerisoy, Mehmet Emin Tuna

Baukosten der Gebäudekonstruktion mit Hilfe von Tunnelschalungen

In der vorliegenden Arbeit wird ein Wohngebäude mit einem auf seitliche Belastungen widerständigem System aus Wandscheiben, die durch eine auf der Anwendung von Tunnelschalungen beruhenden Bautechnologie ausgeführt worden sind, betrachtet. Das Gebäude ist für eine variierende Anzahl von Stockwerken modelliert worden, um mit Hilfe des Models die Technologie in Bezug auf Baukosten zu untersuchen. Der entsprechende Einfluss des Bodentyps ist ebenfalls ermittelt worden. Die erhaltenen Resultate weisen darauf hin, dass Fehleinschätzungen der Bodenkategorie sowohl in der Bestimmung der optimalen Anzahl von Stockwerken als auch im Entwurf konstruktiver Elemente und Fundamente, zu fehlerhaften Entscheidungen führen kann.

Schlüsselwörter:
Baukosten, Anzahl von Stockwerken, Tunnelschalungstechnik, Wandscheibensystem, Bodentypen

1. Introduction

In building construction, it is important to meet functional requirements and to find aesthetical solutions, but also to make decisions considering available resources and economic circumstances. Construction industry differs from other areas in that generated products are very costly and are built only once. Cost estimation is highly significant for engineers working in this industry (either individuals or companies) especially when they have to make decisions to implement/maintain the process, and to use the resources as efficiently as possible [1]. Codes and regulations applied in all countries are also oriented in that direction. Building codes provide a set of rules for economical design that meet minimum strength requirements while using a minimum of resources.

A 60-story building can not be considered equivalent to four superimposed 15-story buildings. Therefore, the selection of structural elements and materials, i.e. the construction cost of the building, changes depending on the number of floors. Unfortunately, some multi-story residential buildings in Turkey are being constructed based on the aforementioned assumption, especially by contractors working on the build-and-sell principle. Because such contractors strive toward profit using simple equations instead of seeking rational applications, significant damages occur either during earthquakes or over time.

At the design phase, all factors that are likely to cause damage during earthquake action should be taken into account, and necessary precautions should be taken. The factors that can lead to earthquake damage can be classified into three groups: earthquake characteristics, structural properties, and soil class. Among these factors, the soil class may cause different levels of damage to buildings, even when they are constructed in adjacent areas within the same project, due to following reasons: (i) soil behavior is not the same under dynamic and static loading conditions, and (ii) soil layers can vary substantially in terms of type, thickness, and groundwater level [2, 3]. Thus the convenience of a construction site should be evaluated based on soil conditions, and should be assessed in parallel with economical solutions. In Turkey, no precise data are available on economic aspects of soil class, although it is a very important factor in the design phase. Only a few studies actually investigated significance of determining local soil class in lateral earthquake load calculations. For example, it has been shown that an error in assessing the soil class may change the lateral earthquake load acting on the building by 25 % for an eight-story reinforced concrete building located in Seismic Zone 3 [4]. The results show that determination of site soil conditions is highly significant in superstructure and foundation design. The effects of soil conditions on construction cost are investigated in this study.

A prototype building, with the structural system consisting of shear walls that can be constructed with a tunnel form system, has been selected. The reason for this is that tunnel form systems are commonly used in residential housing construction because traditional/conventional formwork systems can not meet demands aimed at increasing the number of floors and decreasing the construction time [5]. The goal is to analyze tunnel form projects with respect to construction costs. As a result, cost analyses that are conducted based on findings presented in this study are likely to be of vital significance when design decisions are made.

2. Creating the analysis model

The total of nine building models is generated in this study. All of them are of symmetrical layout and configuration, as presented in the plan view given in Figure 1. The number of floors is changed with an interval of 6 for each model, which leads to 6, 12, 18, 24, 30, 36, 42, 48 and 54 stories.

The analyses were carried out using Sta4-Cad [6], which is a computer program specially designed to perform structural analyses. Static analyses and reinforced concrete calculations were conducted in compliance with TS 500 and 2007 Turkish Earthquake Code [7, 8]. The residential buildings were assumed to be located in Seismic Zone 4 as the idea was to affect the cost as little as possible. Lateral earthquake loads were calculated based on spectral acceleration coefficient, A(T), which is defined as "elastic design acceleration spectrum defined for 5% damping divided by gravity g" and is determined as follows:

$$A(T) = A_0 \cdot I \cdot S(T) \quad (1)$$

where A_o is the effective ground acceleration coefficient and I is the building importance factor, both of which can be obtained from relevant tables given in the code. A_o was taken to be 0.1 for the Seismic Zone 4, whereas I was defined as 1.0 as the modeled buildings are residential structures [8]. Other parameters required in calculations were obtained as follows: spectrum characteristic period (T_A/T_B = 0.15/0.4) since the local site class was assumed to be Z2, seismic load reduction factor (R = 6) because the buildings are shear wall systems, live load participation factor (n = 0.3), live load reduction coefficient (C_z = 1), and model analysis minimum load ratio (B) = 0.9.

In developed countries, such as the European Union member countries or the United States, the concrete compressive strength must not be less than 25 MPa (C 20/25), while C 25/30 and C 30/37 concrete grades are widely used. It is generally accepted that high-quality and sustainable buildings can be built using concrete C 25/30 or higher. Therefore, as the use of a lower-strength concrete would not be appropriate for high-rise buildings, and in order to provide a realistic and valid study, the concrete C 25/30 was used in the analyses.

Minimum shear wall thicknesses were obtained based on static analysis results, which revealed a minimum thickness of 15 cm. The wall thickness was increased in 5 cm increments, while considering applicability of the tunnel form. Table 1 shows shear wall thicknesses for the models with different number of floors.

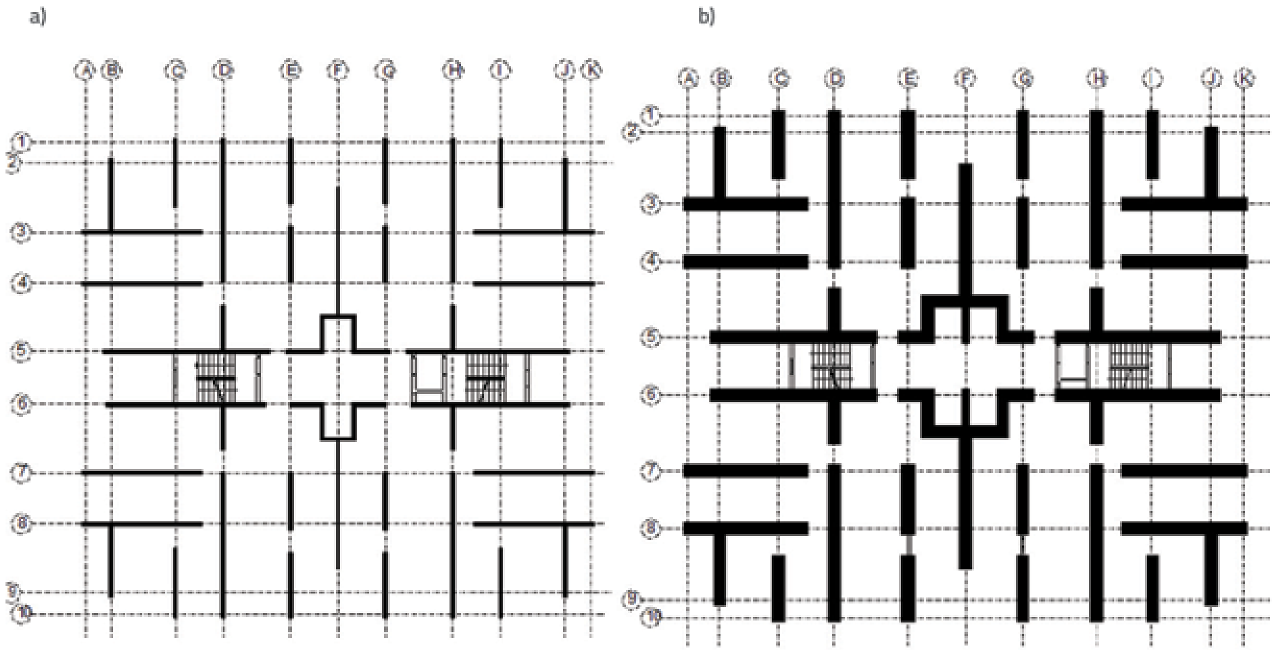


Figure 1. a) Floor plan with two elevators; b) Floor plan with four elevators

The results of the analysis were used to make comparisons on the unit costs per apartment. The number of apartments per building was calculated including all floors, with the exception of basement and installation stories (i.e., only typical floors were analyzed). The distribution of floors and the total number of apartments for each model is shown in Table 2. The number of elevators was doubled in the models with more than 30 stories, because the models were assumed to function as residential housing [9]. Having wider shear wall thickness and higher number of elevators in the taller buildings, the axes of those buildings were slightly expanded in order to maintain "equal size" apartments. After these modifications, apartment sizes differed by 2-3%. However, small differences were neglected in the analysis.

Cost analyses were performed for each model by defining quantities for concrete, formwork, and reinforcement of the structural system (shear walls, slabs, foundation), based on unit market prices [10]. The roof insulation and excavation costs were also included in the analysis. Special prices for the tunnel form used for the superstructure, and the price of pile foundations to be used in case the existing foundations are insufficient, were obtained based on analysis of current market prices. Thus, all assessments were made in compliance with current conditions.

Table 1. Shear wall thicknesses

Number of floors	6	12	18	24	30	36	42	48	54
Shear wall thickness [cm]	15	15	20	20	20	20	40	70	80

Table 2. Distribution of floors in the models

Number of floors	6	12	18	24	30	36	42	48	54
Basement	1	1	1	2	2	2	3	3	3
Structural height [m]	16.80	33.60	50.40	67.20	84.00	100.80	117.60	134.40	151.20
Installation story	0	0	0	1	1	2	2	3	3
Typical floor	5	11	17	21	27	32	37	42	48
Flat	20	44	68	84	108	128	148	168	192

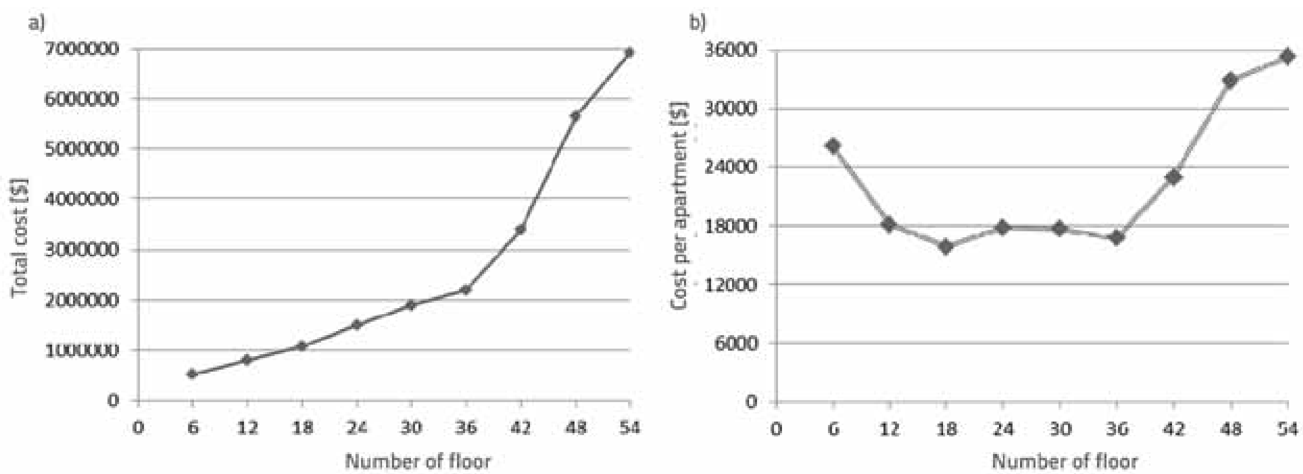
3. Cost analysis

Static soil analyses were carried out for each analytical model (having a different number of floors), all of which consisted of identically sized and symmetrically placed shear walls in both directions. Cost analysis results were then evaluated from two different aspects. First, the models were compared in terms of number of floors regardless of their costs, so as to measure rationality of the tunnel form system. Then the allowable bearing capacity of soil was changed to investigate effects of soil type on the total construction cost.

3.1. Cost analysis of tunnel form buildings with different numbers of floors

For all structural systems, the construction cost is obviously expected to get higher as the number of floors increases. It would however be incorrect to assume that there is a certain relationship between the number of floors and an increase in cost. In fact, there are other important parameters influencing an increase in cost such as the selection of structural system and materials. Therefore, this study investigates construction costs of the projects having allowable bearing capacity of 250 kN/m² and concrete grade C 25/30, while the only variable is the number of floors. Total construction costs of the buildings, as well as the unit construction cost per apartment with respect to the number of floors, are presented in Figure 2.

The comparison of total costs shows that for the design of this geometry (Figure 2), the construction cost for the 6-, 12-, 18-, 24-, 30- and 36-story buildings increases at a stable rate, whereas there is a dramatic rise for the buildings with 42 floors or more. The reason for this rise can be related to the increase in shear wall thickness as the number of floors goes up. This increase can also be observed in Table 1, keeping in mind the fact that the wall thicknesses must meet minimum static requirements. On the other hand, the first striking point in the comparison of unit apartment costs is that the construction cost of a 6-story building is the third highest, following right after the 54 and 48-story buildings. The reason for the high cost of 6-story buildings may be related to the first investment cost of the tunnel formwork. Among the first three models, the lowest cost was obtained for the 18-story building. It has also been noted that for the models of the same wall thickness, the unit cost per apartment decreases as number of floors increases. Some important observations can also be made by comparing construction costs of structural components. Distribution of construction costs of tunnel form components are provided in Table 3 in terms of percentage values.



Variation of cost with respect to the number of floors: a) total costs; b) unit cost per apartment

Table 3. The cost of components as related to the total construction cost

Number of floors \ Components	Formwork [%]	Reinforcement [%]	Concrete [%]	Foundation [%]	Roof [%]	Earth-work [%]
6	43,76	18,06	15,09	16,64	5,18	1,27
12	40,70	23,99	20,00	11,2	3,49	0,86
18	36,59	27,17	24,78	8,37	2,48	0,61
24	33,08	28,41	27,94	7,97	1,80	0,79
30	31,30	32,47	27,96	7,16	1,49	0,90
36	31,08	33,53	28,11	6,19	1,20	0,80
42	22,98	37,77	32,28	5,60	0,85	0,53
48	16,39	40,69	35,90	6,11	0,58	0,36
54	14,72	40,98	36,28	7,55	0,42	0,30

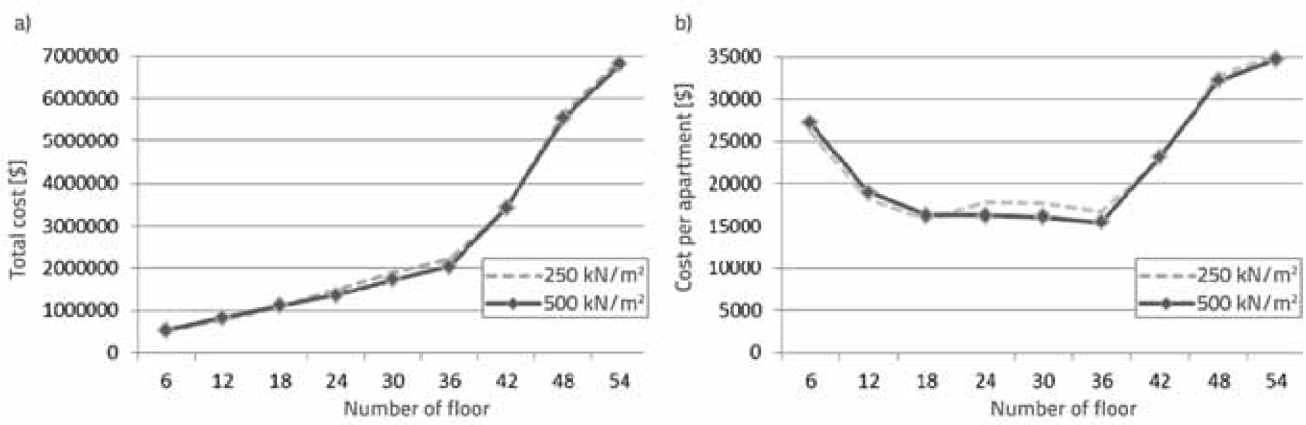


Figure 3. Variation of cost with respect to the number of floors: a) total costs; b) unit cost per apartment

It can first be noted that the ratio of formwork costs to the total cost decreases as number of floors increases. The cost of formwork constitutes almost one half of the total cost for 6-story buildings, whereas this cost amounts to only 17.79% for the 54-story buildings. This shows the importance of selecting the type of formwork in a reinforced concrete building. In fact, selection of the formwork type should be based on economic aspects as it is a significant part of the total cost. It has also been observed that the cost of concrete and reinforcement, relative to the total cost, also gets higher as the number of floors increases. It should be noted that the cost of reinforcement was higher than that of concrete in all models. Therefore, the cost of reinforcement is highly significant. It is in fact the most important item for taller buildings. The cost of formwork occupies the prominent place in cost distribution for buildings with less than 30 floors, whereas the cost of reinforcement becomes dominant as the number of floors increases.

Rational selection of structural system is more important for high-rise buildings because the cost of structural system substantially affects the total construction cost as the number of floors increase. The structural system selection is the most important step in the design of high-rise buildings, as it enables making optimum decisions regarding conditions for which the design will be done, functional demands, etc. In this section, the rationality of structural system is investigated by comparing the number of floors with respect to construction cost for tunnel form projects. It has been concluded that the construction of 42 floors or more is not applicable for the prototype building (in which concrete C 25/30 was used, and the allowable bearing capacity of soil amounted to 250 kN/m^2).

3.2. Cost analysis of tunnel form buildings with different soil types

The stability of soil on which the building will be constructed is very important in the design of high-rise buildings, namely because the loads to be transferred to soil are much higher in such buildings due to a larger number of floors. Another important issue of which design engineers should be knowledgeable is selection of the correct foundation type, as the transfer of vertical and lateral loads to the soil with an appropriate foundation system is a very important concept. The soil has to assume all loads that are applied to the building. For that reason, the type of foundations should be selected based on geological structure of the soil as much as possible. Because the soil type is a very important factor in structural design, this study is also aimed at investigating the effects of soil on construction costs. For that purpose, the allowable bearing capacity (250 kN/m^2) was doubled to 500 kN/m^2, and the two cases were compared.

Based on analysis results, mat foundations should be used whenever soil conditions allow such solution. On the other hand, pile foundations are implemented in cases when stresses due to structural loads are larger than the allowable bearing capacity of soil such that the mat foundation is not capable of assuming such levels of

Table 4. Foundation types used in the models

Allowable bearing capacity	Number of floors								
	6	12	18	24	30	36	42	48	54
250 kN/m^2	Mat Fndn.	Mat Fndn.	Mat Fndn.	Pile Fndn.	Pile Fndn.	Pile Fndn.	Pile Fndn.	Pile Fndn.	Pile Fndn.
500 kN/m^2	Mat Fndn.	Mat Fndn.	Mat Fndn.	Mat Fndn.	Mat Fndn.	Mat Fndn.	Pile Fndn.	Pile Fndn.	Pile Fndn.

Table 5. Relative cost percentages with respect to the number of floors

Relative cost percentages [%]									
Allowable bearing capacity \ Number of floors	6	12	18	24	30	36	42	48	54
250 kN/m^2	100	69,28	60,64	68,23	67,48	63,94	87,85	125,63	135,13
500 kN/m^2	100	69,68	59,89	59,81	59,22	56,84	85,09	118,40	127,87

stress. The risk of liquefaction was neglected, whereas piles were modeled as friction piles, which are designed to resist forces by friction force formed between the soil and the pile. Foundation types used in the models are given in Table 4.

Construction cost comparisons are summarized in Figure 3 so as to show effects of various allowable bearing capacities on estimated construction costs in terms of total cost and unit cost per apartment. Additionally, relative cost percentages for various cases are given in Table 5 so as to compare and highlight conclusions reached during the static analysis.

Total costs were the same for both cases (with two different allowable bearing capacities) for 6-, 12-, and 18-story buildings as the foundation system did not need to be changed. The difference was however observed for 24-, 30-, and 36-story buildings. The reason for the difference is the use of pile foundations for buildings with 24 floors and more, when the allowable bearing capacity was 250 kN/m^2. However this system was used only for the buildings taller than 42 stories when the allowable bearing capacity amounted to 500 kN/m^2. Comparisons of unit costs per apartment primarily show that the most appropriate number of floors is 18 when the allowable bearing capacity is 250 kN/m^2, whereas this number increases to 36 when the allowable bearing capacity is 500 kN/m^2. To further explain the conclusions reached via the static analysis, relative cost percentages of different cases are presented in Table 5. As can be seen from Table 5, the cost of a 6-story building is taken to be 100 percent. According to this approach, the most feasible case per unit floor is an 18–story building with the percentage of 60.64 for foundations with 250 kN/m^2 of bearing capacity, and a 36–story building with the percentage of 56.84 for foundations with 500 kN/m^2 of bearing capacity. Similarly, it has been concluded that the number of storeys of 48 and more can be regarded as economically unprofitable.

It is obvious that a mistake in determining the local soil class would cause misleading results in the design of structural components and foundations. It can also be noted that when the allowable bearing capacity is higher, costs increase dramatically for buildings with more than 42-stories. Therefore, it can be concluded once again that the construction of buildings with 42 floors or more would not be rational.

4. Conclusions

In construction industry, the financial model of the project should be accurately established during the decision making process, so as to enable adequate handling of potential problems due to cash flow, and to prevent loss of national resources. This can only be achieved by accurate estimation of total costs already at the pre-design phase. The distribution of costs varies depending on the structural system selected for the building, and on the size and type of structural elements.

In recent times, the use of tunnel formwork systems in the construction of multi-story reinforced concrete buildings has become very common in Turkey. Design engineers should not only be knowledgeable of design principles, but should also be familiar with economic aspects of tunnel form systems. The effects of the number of typical floors and local soil conditions on the structural design and total cost should be estimated ahead of time. Project investors would like to know the budget in order to secure adequate financing for the investment. It is therefore important to make realistic cost estimations as soon as practicable. Analyses of a number of tunnel work projects, consisting of a number of different parameters, were conducted in this study. Cost analysis results are summarized as follows:

- It was concluded that, due to significant increase in construction costs, 42 floors and above would not be rational for shear wall buildings (or similar structures) constructed using tunnel form systems. In cases when the number of floors is not selected in accordance with the structural system, the design of structural components results in larger element sizes, which in turn causes losses in terms of material. As the thickness of shear walls increases, the total building weight also increases, which is why more expensive foundation systems must be used and more reinforcement must be placed. The reason for the increase in shear wall thickness can be related to greater displacements as the building becomes taller, i.e., thicker walls are needed to provide rigidity and to prevent excessive drift of taller buildings. The size of structural elements should not be increased significantly, and larger lateral (earthquake and wind) loads due to increase in height should be taken into account by selecting an efficient structural system instead of using larger element size

- Although the total construction costs increase continuously with an increase in building height, the distribution of components constituting the total cost varies considerably. Comparison of models with identical parameters has revealed that the proportion of the concrete and reinforcement costs relative to total cost increases with an increase in the number of floors. It was established that the most costly component is the reinforcing steel. On the other hand, the proportion of formwork costs decreases with an increase in the number of floors, which is a clear indication that the use of tunnel formwork is justified in case of high-rise buildings.
- Because formwork costs constitute an important portion of the total cost, the formwork type should be selected based on economic aspects. The rationality is an important feature of tunnel form systems which have been increasingly used in the recent years. Design engineers should be aware of the availability and restrictions in order to take full advantage of this technology. For example, analytic results obtained in this study show that use of tunnel form systems is not rational for low-rise shear wall buildings due to very high unit costs per apartment. Therefore, tunnel form systems are more advantageous in mass housing constructions since the life span of tunnel formwork is longer compared to conventional formwork systems, although initial investment costs are higher. It should also be noted that the use of traditional timber formworks may be more economical and preferable for relatively small-scale construction projects.

It can be concluded that tunnel form systems, which are widely used in the construction of reinforced concrete shear wall buildings, lose rationality based on the criteria presented in this study. This paper attempts to provide helpful recommendations to design engineers through comparison of different models with appropriate criteria.

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