Project Budget Comparison of a Conventional Building and a Seismically Isolated Building

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Abstract There have been numerous studies in the past three decades about seismic isolation in the field of structural and earthquake engineering. However the studies that take into account economical aspects of implementing seismic isolation to the structures are very rare. In this study, firstly the costs of both conventional and seismically isolated buildings are calculated. Then, the seismically isolated and conventional buildings are compared in terms of their seismic performance and the project budget. Finally, the results of the seismic performance and the cost benefit are presented and discussed. It is obtained from this paper that, although the initial construction cost of the seismically isolated structure is obviously more than the conventional building, eventually in a possible earthquake scenario seismic isolation may provide financial advantage over the conventional building case.

Keywords Seismic Isolation · Project budget · Earthquake · Cost Analysis

1 Introduction

One of the most important challenge in civil engineering is to control the structural vibrations. The major aim of the earthquake codes and the specifications is protecting the structures from the hazards caused by earthquakes. There may be a loss of the serviceability of the building due to extreme accelerations and displacements that the structure may experience. These accelerations and displacements may exceed the limitations that are specified by the codes. Some types of structures are more crucial than the others. Important structures such as hospitals, power plants, municipality buildings, and fire stations have to be operational both during and after the earthquake movement. The usage of seismic isolation has been more common in these kinds of structures. Furthermore, in Turkey, seismic isolation is mandatory for

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the state hospitals according to Turkish Building Earthquake Code 2018 (TBDY-2018). Although the usage of seismic isolation is also advantageous for residential buildings, in Turkey seismic isolation implementation to those kinds of buildings recently started. Past earthquake experiences showed that many reinforced concrete structures experience damages partially or entirely during an earthquake.

Generally speaking, the seismic isolation concept is relatively new compared to the conventional design method. Because of this fact, we focused on the recent studies, especially published after 2015. More specifically, the research was conducted in terms of seismic and cost performance of seismically isolated structures and the conventional structures. Thanks to the literature review, the results show that the seismic isolation is used for different types of structures such as nuclear power plants, bridges, hospitals and buildings. The core objective of performance-based design of buildings is to transfer earthquake demands on the structural elements [1]. To achieve this, the predominant period of the structure should be long. For the high-rise building, the implementation of the seismic isolation is not beneficial and feasible because of the fact that the natural predominant vibration period of the high-rise buildings is already long. Seismic isolation is a commonly applied technique to reduce structural and nonstructural damage during severe earthquake excitation [2]. External energy dissipation devices and base isolators extend the natural period of the buildings and add additional damping for the building.

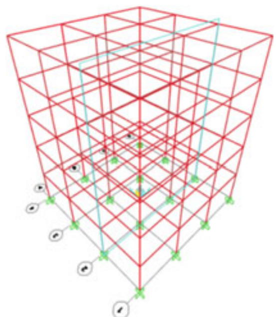
In the scope of this research, we investigated the research that contain the analysis of a 5 story building in terms of not only the earthquake performance but also the cost analysis. There are a few studies that cover the cost effectiveness of the utilization of the seismic isolation among the reviewed literature. Plenty of studies only deal with the initial and construction cost of the studies. The study of [3] shows that the cost benefit of base isolation is barely discoverable because of the high initial cost. Moreover, an indicator of structural seismic performance based on life-cycle cost for a 7-story hospital building was proposed in [4]. In the light of the literature review, despite the papers related to the seismic isolation, there is no concrete knowledge on direct comparison of seismically isolated and fixed base residential building in terms of earthquake and cost performance. On the other side, [5–7] were the valuable references for this review. While the two of them, [5, 7], focused on the comparison of base isolated three and six-story reinforced concrete buildings, the other one, [6] analyzed the earthquake performance and retrofitting cost of base isolated 4, 6, and 8 story reinforced concrete buildings. As a result of the literature review, it can easily be realized that the knowledge regarding to the comparison of fixed-based and isolated buildings in terms of both earthquake performance and cost benefit is still limited. According to this outcome, this research focuses on the lack of knowledge stated above. This study will compare two different types of buildings by considering the earthquake performance and cost.

This study concentrates on two different parameters that are earthquake performance and the project budget of a building. Initially, a 5-story reinforced concrete building is modeled according to TBDY 2018 which is the current earthquake code valid in Turkey. The seismic behaviour of the structures is analyzed to determine the earthquake parameters including lateral displacements, and inter-story drifts for the different cases with and without seismic isolation. SAP 2000 software is used for testing the models. On the other hand, this research focuses on the financial part of the structure as a secondary perspective. It is recommended that cost estimation should be performed before the start of a construction. Since every construction project is unique, the estimations differ from one project to another. In the very beginning of a project, the design method has to be determined. The design method is directly related to the project budget. The difference on the selection of the building material as steel, reinforced concrete or timber has a huge impact on the material cost of the project. Moreover, the usage of relatively new methods such as implementation of dampers and seismic isolators may significantly change the project budget. In this study, the project budget is calculated for cases that are; a conventional building and a seismically isolated building. The approach for cost estimation is chosen as activity-based cost analysis.

2 Numerical Example

In this section, information of the numerical example is presented. The example building performance is evaluated in terms of earthquake behavior and project cost. Moreover, structural system does not include shear walls. The model can be considered as a frame system. Frame system is basically defined as a structural system that contains only columns and beams. Effective stiffness factors of reinforced concrete structural system elements are chosen for columns and beams as 0.7 and 0.35 in a respective way. Figure 1 shows the 3D view of the model. It should be noted here that this paper is derived from the master thesis of the first author [8]. More information about this subject can be obtained from [8].

Fig. 1. 3D View of 5 story fixed-base building



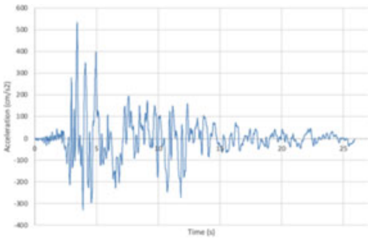


Fig. 2 Acceleration time history of Duzce Earthquake

2.1 Structural Material and Dimensioning of the Building

The building material is chosen as reinforced concrete. The usage of concrete with a compressive strength less than 25 MPa (C25 concrete) is prohibited by the TBDY 2018 specification for all type of structures that are going to be constructed in Turkey. In this study the compressive strength of concrete is chosen as 30 MPa with an elasticity modulus of 32,000 N/mm^2. For the seismically isolated case, lead rubber isolators are chosen and modelled in SAP2000 as link/support elements. Rubber diameter of seismic isolator is 500 mm. Total overall height including external plates is 167 mm. Overall plate size is 550 $\times$ 550 mm. Total rubber thickness 77 mm. While the vertical stiffness is 885 kN/mm, the effective horizontal stiffness is 1.6 kN/mm. The building that is analyzed in this section is chosen as five-story residential reinforced concrete structure. Dimensions of the structure are chosen as 12 $\times$ 12 m in plan. There are 4 axes in both x and y-direction. The distance between axes is 4 m. Symmetric floor plan was preferred to eliminate eccentricity, the dimensional, and directional effects. While the dimensions of the columns are selected as 60 $\times$ 60 cm, beams are modelled as 30 $\times$ 60 cm. Lastly thickness of the slab is chosen as 15 cm.

2.2 Earthquake Used in the Dynamic Analysis

Duzce Earthquake (1999) that was occured on North Anatolian Fault (NAF) fault in Turkey with a moment magnitude of 7.2 is used in this study. Since NAF is a right lateral strike-slip fault, East–West component of this earthquake is chosen for the time history analysis. Acceleration time history of this earthquake is shown in Fig. 2.

2.3 Results of the Dynamic Analysis

The support condition is modelled as fixed support in Case 1, link support is preferred for modeling seismic isolation case which is Case 2. For Case 2, model is revised by alternating support condition. In earthquake engineering, the first phenomenon to take into account is the modal periods of the structure. Table 1 shows the first

Table 1 Modal periods and frequencies of the FB building

	Period (s)	Frequency (s^{-1})
Mode 1	0.4535	2.2049
Mode 2	0.4535	2.2049
Mode 3	0.3972	2.5178

Table 2 Modal periods and frequencies of the SI building

	Period (s)	Frequency (s^{-1})
Mode 1	1.9890	0.5028
Mode 2	1.9890	0.5028
Mode 3	1.8088	0.5528

3 modal periods and the frequencies of the 5-story fixed base building (FB), Table 2 presents the modal periods and frequencies of seismically isolated building (SI). While the fundamental period of the FB building is approximately 0.45 s, it is about 1.99 for the SI case.

One of the key parameters in analyzing a structure for earthquake engineering discipline is the displacement of the structure under an earthquake. To ensure the life safety of the residents, the story drift must be under control. Design engineers have to check the displacements to make sure if they are in the tolerable limits or not. The maximum story displacements and comparison of the inter story drifts are presented in Fig. 3 and Fig. 4 respectively. According to the results of the analysis, the displacement of the isolation level is 93 cm. Figure 3 shows the displacement comparison for both cases. The isolation level displacement is subtracted from each story while constructing this figure. As expected, the changes between each story displacements are not the same. The difference in the first story is about 8%. This ratio is increasing while elevating from the first to fifth story. The change between fifth story displacements is 41%. Seismic Isolation has a great impact on decreasing inter story drifts as it can be seen from Fig. 4.

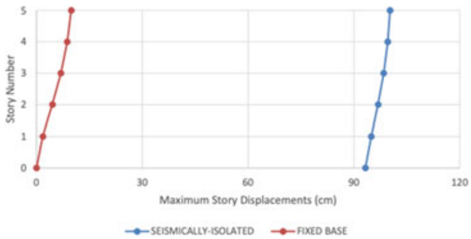


Fig. 3 Comparison of maximum story displacement

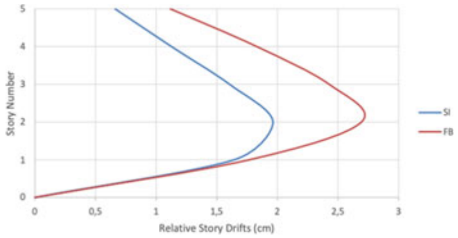


Fig. 4 Comparison of inter story drifts

3 Cost Analysis

Without a doubt, cost is one of the most important phenomena all around the world in all sorts of business. Finance affects decisions significantly on different sectors. As well as the other industries, it is also important for the construction sector. It is not possible to construct a building without considering its financial part. As it was performed for the earthquake analysis part, cost comparison is made for two different cases which are the conventional and seismically isolated building. It is known that there are several methods for cost calculation. In this paper the activity base costing technique is chosen for comparison purposes.

3.1 Activity-Base Cost Calculation

Activity-Base Cost Calculation is one of the most important costing approaches that are used for the calculation of a construction project. In contrast to the problems related to the traditional cost methods, activity-based costing system has been developed as an alternative approach and has become widespread in time with the developing technology. The most important benefit of this system is that activity-based costing systems provide more realistic product cost information in comparison with the traditional cost methods.

3.2 Establishing the Work Breakdown Structure of the Case Project

Before the market research of unit prices, work breakdown structure is established for the 5-story residential building. Undoubtedly, applying seismic isolation has financial consequences. However, it is very beneficial to enhance the earthquake performance of structures. On the other hand, it increases the cost of the construction due to its advanced technology. Static project cost for seismically isolated building is higher than the fixed base building because the design engineers that work on seismically isolated buildings are rare. In addition, the design of a structure with

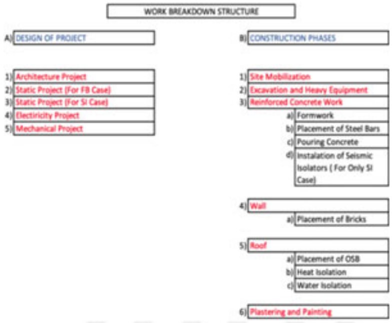


Fig. 5 Work breakdown structure (WBS)

seismic isolation requires more efforts. Static project cost is calculated for both cases (FB and SI) and presented in Fig. 5. The only difference between the FB case and SI case is the installation of the seismic isolators to the related level of the building. Seismic isolators must be implemented on each column above the foundation level. Basically, SI structure needs 16 seismic isolators for installation. Furthermore, two more isolators are necessary for the prototype testing before the construction starts.

3.3 Market Research and Pricing

After the work breakdown structure is completed, market research is carried out for determining the unit prices. Unit prices are determined for the resources which are materials and labor. Quantity calculations are made for structural construction activities. Unit prices are multiplied by their related quantities to obtain the cost of each activity. In contrast with the structural construction, fine construction cost estimation is not carried out in a very detailed way. It is not completely possible to calculate the cost of each fine construction activities. According to the investigation of a real building project, the ratio between the structural construction and fine construction is calculated. Three different approaches that are mentioned just before are applied to estimate the cost of the reference building. Considering the date of May 24, 2021 1 $ was equal to 8.40 Turkish Lira ₺ and 0.82 EUR) the total cost of the building is found as ₺1,139,788.00 ($135,750.5) according to the Turkish Republic Ministry of Environment and Urbanization’s Unit Price Chart, and it costs ₺1,365,297.50 ($162,608.9) by referring to the private sector prices. These prices were calculated by considering the economic conditions in April 2020. To make the cost up to date, the inflation rate of 17.14% that was announced by Turkish Central Bank is used. The effect of inflation is included in the cost estimation. Updated cost estimation is obtained as ₺1,597,612.63 ($190,278.1). It is predictable that the number of the seismic isolators affected the project budget dramatically. Due to the seismic design procedure, prototypes are manufactured and tested before the installation. As the structural system has 16 columns on each floor,18 pieces of seismic

Table 3 Total and m^2 costs (reference date: May 24, 2021)

Building Type	Cost Type	Ministry ($)	Private Sector ($)	Updated ($)
FB	Total	135,750.5	162,608.9	190,278.1
FB	m^2	188.5	225.8	264.3
SI	Total	191,685.1	218,633.6	246,408.5
SI	m^2	266.2	303.7	342.2

isolators are needed. Price of an isolator is 2500 EUR ($3050.8). It corresponds to the ₺25,625.00 by taking the EUR/₺ rate as 10.25 on 24 May 2021. Another cost item is the design of the static project cost. It can be known that the design of SI structure is more expensive than the design of FB structure. The difference between the design cost prices for each meter square is ₺5.50. These differences are added to the FB project cost. The comparison of the total and m^2 costs is shown at Table 3 in USD currency. It should be noted here that the isolators are not prone to corrosion which happens in some other types of materials due to the water and humidity. However, only the steel plates and connecting bolts which are attachment elements to the superstructure and the substructure should be checked periodically. In addition, since it does not affect the ultraviolet (UV) rays under the buildings, the rubber does not have any disadvantage depending on its UV resistance. For these reasons, the maintenance cost of lead core rubber isolators is dramatically lower than the other construction costs. Therefore, the maintenance cost of isolators is being excluded in this paper. It can be advised that the visual inspection shall be carried out after major earthquakes or within 10-year periods.

According to the ministry price list, seismic isolator cost is approximately 28% of the total construction cost. If the private sector prices are considered, the share of the isolation is being 25%. Lastly, seismic isolation expense is 22% of the total cost if the updated prices are being taken into account. Although the total construction area is relatively less and the number of the seismic isolator is 18, the ratio of SI Cost/Total Cost of 22% seems to be feasible. Conclusions obtained from this study are given below.

4 Conclusion

In this paper, it is obtained that seismic isolation implementation reduced the top story displacement (the most critical floor in terms of earthquake effects is the top floor) of the building about 69%. Financial results shows that seismic isolation increases the total project cost by 29.12% according to up-to-date prices. For the example building with seismic isolators, although the cost of the project is increased by 29.12%, the top story relative displacement is reduced by 69% under the seismic excitation. The cost increase is relatively high, however it should be noted that the benefit of seismic isolation implementation is very significant. The decrease in the inter story drift of each story shows that the structural elements are not experiencing any serious damages. Therefore, the failure of the structure due to the earthquake excitations is prevented. In addition, the functionality of the structure is sustained, and the residents of the building may not even feel the earthquake shaking. Furthermore, the reduction of the structural vibrations may save the equipment, electronical devices or valuable things that are in the building. These are considered as secondary advantages of seismic isolation usage. Another advantage is that the seismic isolation not only may prevent the collapse of the structural system but also may save the house furniture and valuable goods.

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