



Experimental and Numerical Investigation of Steel Industrial Structures under Different Soil Classes

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Keywords

Soil class,
Shake table test,
Seismic performance,
Time-history analysis,
Structural steel quantity,
Steel industrial structures.

Abstract

Steel industrial structures are widely preferred in seismic regions due to their high strength-to-weight ratio, rapid construction process, and ductile behavior characteristics. However, soil conditions and seismic hazard levels have significant effects on the seismic response and structural steel demand of these systems. In this study, the effects of different soil classes on the seismic performance and structural steel quantities of steel industrial structures were investigated through both numerical and experimental approaches. The analyses were conducted for the provinces of Eskişehir, Edirne, İstanbul, and Yalova in Türkiye by considering ZB, ZC, ZD, and ZE soil classes defined in TBEC 2018. Numerical analyses were performed using SAP2000 software through modal analysis, equivalent seismic load analysis, and response spectrum analysis. In addition, shake table tests were carried out to qualitatively evaluate the dynamic response characteristics of the structural model under different earthquake records and soil conditions. The results indicated that interstory drift ratios, λ coefficients, acceleration amplification, and displacement demands generally increased with the deterioration of soil conditions. Higher acceleration and displacement responses were obtained particularly for the ZE soil class. The findings also showed that soil-dependent seismic parameters significantly influence the dynamic behavior of steel industrial structures. Furthermore, the required amount of structural steel varied depending on both seismic hazard level and soil class. While significant increases in structural steel quantity were observed for some cities, more limited variations were obtained for others. Overall, the results demonstrate that soil class and seismic demand parameters play an important role in the seismic performance and structural steel requirements of steel industrial structures and should be carefully considered during the design process.

1. Introduction

Earthquakes are considered a type of natural disaster that occurs as a result of tectonic processes in the Earth's crust. They pose a considerable danger for structural safety. Therefore, it is necessary to consider seismic loading of a structure in areas that are located along the fault line. Because it is located in the Alpine-Himalayan belt, Türkiye faces high seismic hazards caused by active fault systems such as the North Anatolian Fault Zone (NAFZ) and the East Anatolian Fault Zone (EAFZ) [1–3]. Thus, there is an urgent need to assess the impact of earthquakes on structures and to determine optimal methods for estimating their seismic response. The intensity of an earthquake depends not only on the moment magnitude but also on ground motion characteristics and soil conditions. Such phenomena as soil amplification, liquefaction, and soil-structure interaction are capable of significantly changing accelerations and forces imposed on structures [4–5]. Different soil classes may lead to variations in seismic demand through soil-class-dependent spectral parameters defined in TBEC 2018, resulting in different force and displacement demands on structural systems [5,6,18]. Recent major earthquakes have shown that design spectra might underestimate seismic effects causing a significant load increase for a structure [6]. Thus, the seismic behavior of a structure depends both on soil conditions and structural characteristics. Structures having great ductility and high energy dissipation capabilities will perform better under earthquakes [7,8,13]. In such circumstances, it becomes clear that steel structures are preferable in terms of seismic safety since they demonstrate high strength, ductility, and energy absorption [7,9,13]. Steel industrial structures are commonly used in facilities that require large spans such as warehouses, factories, hangars, and logistic centers due to fast installation, prefabrication, and lightweight of the structure [9,10]. Higher seismic demands associated with different design spectra may lead to increased member sizes and consequently higher structural steel quantities [11,17]. The literature review shows that the stiffness, ductility, and energy dissipation capability of the structural system have considerable importance in assessing seismic behavior of the structure [7,9,13]. At the same time, few studies examine the connection between seismic parameters and structural steel requirements. For example, studies evaluating variations in structural steel quantities of steel industrial structures depending on soil class and seismic hazard level are still limited.

Experimental research is important in analyzing the behavior of steel structures under earthquakes. Among experimental methods, shake-table testing is frequently used because it enables the investigation of structural response under controlled earthquake excitations and provides valuable insight into the dynamic behavior of structures. [14–16]. Additionally, time-history analysis and numerical models using the method of finite elements make it possible to conduct a detailed analysis of structural behavior [9,19,20]. Studies concerning structural steel demand indicate that the economic feasibility of steel structures depends on structural parameters, among which seismic effects play a decisive role. Thus, it is reasonable to conclude that structural steel quantity estimation is closely connected to parametric studies and design codes [6,11,12].

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Accordingly, the main aim of this research is to investigate the influence of TBEC 2018 soil-class-dependent seismic parameters on the seismic response and structural steel quantity of a selected steel industrial building located in different Turkish cities. The study presents a code-based parametric assessment using numerical analyses and supporting shake table tests [21,22].

Unlike previous studies that mainly focus on either structural performance or experimental investigations, the present study evaluates the effects of different soil classes and seismic conditions on both the seismic response and structural steel demand of a steel industrial building. Numerical analyses and shake table tests are used together to provide a comparative assessment of structural behavior under different seismic scenarios. Therefore, the study contributes to understanding the influence of soil-dependent seismic parameters on both structural performance and structural steel requirements.

2. Material and method

For this study, a combination of numerical and experimental approaches were used in examining the performance of steel industrial buildings subjected to seismic forces. This involved conducting the experiment with respect to various soil conditions and earthquake loading scenarios, along with a numerical analysis using the finite element approach. Specifically, the steel industrial building was modeled using SAP2000 and subjected to various earthquake loading scenarios. In the case of the experimental work, the dynamic response of the structure was investigated via shake table tests, which will then be used in evaluating the results from the numerical analysis approach.

2.1. Structural information

The steel industrial structure model used in the analysis refers to wide-span and single-story structural systems. The geometric properties of the structure in analysis remained constant throughout the whole analysis process. However, in order to guarantee that design conditions are met in all cases, cross-section properties of the load-carrying systems have been modified accordingly. The objective of the study was not to compare the response of a single fixed structural configuration under different soil classes. Instead, each city-soil class combination was designed to satisfy the requirements of TBEC 2018, and the resulting code-compliant structural systems were subsequently compared in terms of seismic response and structural steel quantity. Therefore, structural steel models were developed for each soil class to satisfy design conditions, and the required steel quantities for each structure were analyzed separately. Load-carrying systems were selected from among steel building framing systems according to the provisions of Türkiye Building Earthquake Code (TBEC 2018). Two different systems were chosen for this purpose. In these two systems, the effect of earthquake loading was completely transmitted via highly ductile and moment transferring steel frame system, and the effect of earthquake loading is also transmitted via highly ductile central diagonal steel frames. The reason for selecting these systems was their common usage in industry and load-carrying ability. Finite element analysis of the structure was performed using SAP2000. Geometric properties and characteristics of steel industrial structure model, and the data about these can be found in Table 1. Three-dimensional view of steel structural model and load-carrying system is illustrated in Figure 1.

Two different lateral load-resisting systems were considered in the study in accordance with TBEC 2018. The first system was modeled as a Special Moment Resisting Frame (SMRF) with a behavior factor of $R = 8$, while the second system was modeled as a Concentrically Braced Frame (CBF) with a behavior factor of $R = 5$. All moment-resisting frames were modeled with rigid beam-to-column connections to ensure moment transfer between structural members. Releases were assigned to concentrically braced members, purlins, and secondary beams in accordance with their structural behavior. Wind columns located at the two end facades of the building were modeled as leaning columns, while all column bases were assumed to be pinned connections. Flexible diaphragm assumptions were adopted in all models. Geometric nonlinearity effects were considered through $P-\Delta$ analysis using a dedicated $P-\Delta$ load case in SAP2000. A damping ratio of 5% was used in all analyses. Modal analysis results indicated that the cumulative modal mass participation ratios exceeded 97% in the principal horizontal directions, satisfying the requirements of TBEC 2018. The seismic analyses were performed in accordance with TBEC 2018, while steel member design and verification were carried out according to the provisions of AISC 360-16 Specification for Structural Steel Buildings.

The numerical models were developed using SAP2000 Version 25. The mass source was defined by considering dead loads (DEAD), wall loads (COVER-WALL), 30% of the snow load (SNOW), and 30% of the roof live load (LROOF). Steel member design was performed according to the LRFD (Load and Resistance Factor Design) provisions of AISC 360-16. The Direct Analysis Method together with General Second-Order Analysis was adopted in the design procedure. Serviceability limit-state combinations (SLS), P-DELTA combinations for second-order effects, and YDKT load combinations for strength design were defined in the model. For each city-soil class combination, member sections were iteratively updated until the code requirements related to strength and interstory drift limitations were satisfied. The final member sizes obtained after the design process were subsequently used in the seismic performance evaluations and structural steel quantity calculations.

Table 1. Structural and material properties of the investigated steel industrial structure

Parameter	Model
Structural system type	Braced steel frame system-Concentrically Braced Frame
Plan dimensions	24 m × 42 m
Number of stories	1
Building height	8 m
Total height	9 m
Main columns	HEB 340 – HEB 650
Main beams	HEB 340 – HEB 650
Tie beams	HEB 120 – HEB 140
Wind columns	HEA 300
Bracing elements	CHS 139.7×5 – CHS 168.3×6
Purlins	UPN 160
Steel material class	S235JR - S275JR
Soil classes	ZB-ZC-ZD-ZE

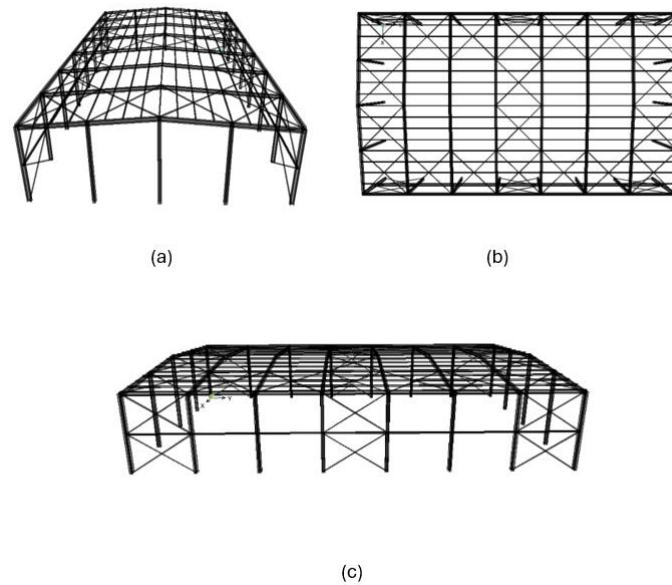


Figure 1. Three-dimensional views of the steel structural model: (a) front view, (b) top view, and (c) side view

2.2. Numerical analysis method

Numerical studies were performed for the assessment of the behavior of the steel industrial structure model under seismic loading conditions. The studies comply with the Türkiye Building Earthquake Code (TBEC 2018), and the structure model was modeled using SAP2000 software through the finite element method. The equivalent seismic load method was employed to assess the structural behavior subjected to seismic impact, and studies were performed separately for different soil classes [6].

Local seismic factors used in the study were estimated based on TBEC 2018 code provisions. Spectral acceleration factors, local soil influence factors, and earthquake ground motion parameters that were taken into consideration for performing numerical studies were defined according to the required code provisions [6]. Analysis factors were estimated considering the seismic hazard features of the region where the structure is located, and these factors are indicated in Table 2.

Table 2. Local seismic parameters used in the analyses

City	Soil Classes	S_s	S_1	S_{ds}	S_{d1}	T_a	T_b
Eskişehir	ZB	0.307	0.131	0.276	0.105	0.076	0.380
Eskişehir	ZC	0.307	0.131	0.399	0.197	0.099	0.494
Eskişehir	ZD	0.307	0.131	0.477	0.306	0.128	0.642
Eskişehir	ZE	0.307	0.131	0.688	0.514	0.149	0.747
Edirne	ZB	0.667	0.204	0.6	0.163	0.054	0.272
Edirne	ZC	0.667	0.204	0.823	0.326	0.079	0.396
Edirne	ZD	0.667	0.204	0.845	0.447	0.106	0.529
Edirne	ZE	0.667	0.204	0.956	0.669	0.140	0.700
Yalova	ZB	1.513	0.393	1.362	0.314	0.046	0.231
Yalova	ZC	1.513	0.393	1.816	0.59	0.065	0.325
Yalova	ZD	1.513	0.393	1.513	0.749	0.099	0.495
Yalova	ZE	1.513	0.393	1.21	0.954	0.158	0.788
İstanbul	ZB	0.871	0.242	0.784	0.194	0.049	0.247
İstanbul	ZC	0.871	0.242	1.045	0.363	0.069	0.347
İstanbul	ZD	0.871	0.242	1.003	0.512	0.102	0.511
İstanbul	ZE	0.871	0.242	1.048	0.748	0.143	0.714

Note: SDS and SD1 are expressed in g units.

T_a and T_b denote corner periods defined according to TBEC 2018.

The environmental loading on the structural model was done as per the relevant standard and code requirements. In this regard, the analysis was done by considering dead loading, live loading, wind loading, and snow loading as required. The loading amounts and the combination of loads used during the analysis are shown in Table 3.

Table 3. Environmental load parameters used in the analyses

City	Maximum Ambient Temperature	Minimum Ambient Temperature	MGM Snow Load	TS 498 Snow Load	MGM Wind Speed	TS 498 Wind Speed
Edirne	32.0 °C	-19.5 °C	50 cm	0.75 kN/m ²	28.9 m/s	28 m/s
Eskişehir	30.2 °C	-19.5 °C	30 cm	0.75 kN/m ²	28.3 m/s	28 m/s
Yalova	28.6 °C	-11.0 °C	50 cm	0.75 kN/m ²	22.8 m/s	28 m/s
İstanbul	29.7 °C	-9.0 °C	41 cm	0.75 kN/m ²	20.8 m/s	28 m/s

As per the Equal Seismic Demand concept, the effect of horizontal loads on the structure due to an earthquake was obtained using the approach stated by TBEC 2018 and implemented in the numerical model to act on the structural mass. The factors affecting the seismic loading include but not limited to the structure period, spectral acceleration coefficient, and behavior factors. In this case, considering the evaluation of the structural load-bearing system to be that of a highly ductile moment resisting steel frame and a highly ductile centrally braced steel frame as mentioned in the Türkiye Building Earthquake Code (TBEC 2018), the behavior factors, $R=8$ and $R=5$ respectively, were considered.

The value of the structural period was obtained using Equation (1) using the approximation method and verified against the limit values in the code [6]

$$T_{pA} = C_t \cdot H_N^{\left\{\frac{3}{4}\right\}} \quad [1]$$

Within the scope of the equivalent seismic load method, the base shear force was calculated using Equation (2) [6].

$$V_{TE} = m_t \cdot S_{AR} \cdot (T_p) \quad [2]$$

In addition, the condition given in Equation (3) was satisfied to ensure that the calculated base shear force did not remain below the minimum value specified in the code.

$$V_{TE} \geq 0.04 \cdot m_t \cdot I \cdot S_{DS} \cdot g \quad [3]$$

During the analyses, interstory drift ratios and λ (lambda) coefficient checks were performed to evaluate the compliance of the structural behavior with the code requirements. The interstory drift values were compared with the limit value given in Equation (4), and the structural performance was evaluated accordingly.

$$\Delta_i \leq 0.008 \cdot h_i \quad [4]$$

Moreover, the secondary effects were expressed through the factor λ , whose value was estimated to evaluate structural stability and determine whether the structural design complied with the limit values defined in the regulation.

Also, to facilitate the examination of structural behavior apart from the equivalent seismic loading method, time-domain analyses were performed in this study. In the time-domain analyses, the real-life acceleration-time histories of earthquake motions were directly used in the structural analysis, resulting in the dynamic responses of the structure.

2.3. Experimental setups

Within this study, experimental studies have been carried out to investigate the dynamics of a steel industrial building model subjected to seismic loads. In experimental studies, tests of the structural model have been done on a shake table test device. The acceleration and displacement responses of the structural model due to real earthquakes recorded in the system software and sent to the shake table have been obtained. These data have been assessed together with numerical analysis results. This was done to present the seismic response behavior of the structure model in a more realistic way.

In order to conduct a more realistic evaluation of the dynamic behavior of the structure model under seismic loading conditions, experiments on the shake table were performed. The test machine employed in these experiments consists of a servo motor actuator, and the dimensions of the table plane area, vertical load capacity, travel, maximum free table acceleration, and velocity are 2000 mm × 2000 mm, 1.5 tons, 200 mm, 4g, and 500 mm/s, respectively. Seismic loads were provided through the definition of the real accelerations to the shake table via control software. In experimental studies, acceleration and displacement responses of the structure model were recorded with a multichannel data acquisition system. Acceleration measurements were made with $\pm 8g$ -capacity accelerometers installed in different parts of the structure. Displacements were detected by LVDT sensors having 200 mm capacity. A summary of the measuring devices is given below in figure 2.

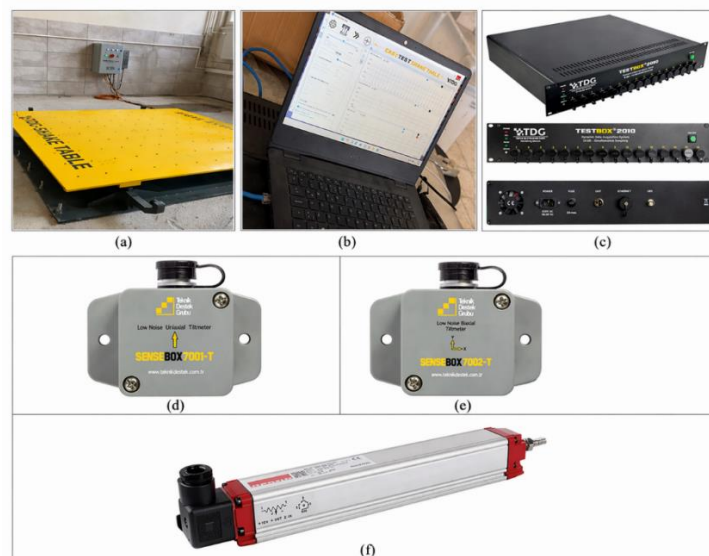


Figure 2. Measurement system components used in the experiments: (a) shaking table, (b) software program, (c) data acquisition unit, (d) single-axis accelerometer, (e) two-axis accelerometer, and (f) LVDT (displacement sensor)

In the experimental analysis, the steel structural model was mounted on a shake table to construct the experimental setup. To subject the structural model to horizontal excitations, some specific acceleration recordings which are equivalent to earthquakes were used in the test process. For the shake table test, a rigid connection was formed between the structural model and the shake table for proper force transmission.

On the other hand, in the experimental test set up, a set up arrangement was adopted that considers the geometry and boundary conditions of the structural model. Using the installed measuring system, acceleration and displacement were simultaneously measured while the structural model was subjected to simulated earthquake effects. All the earthquake accelerations considered in this study have been adjusted depending on the capacity of the shake table. Figure 3 below shows a general picture of the test set up arrangement.

The shake table tests conducted in this study were not designed to provide a direct validation of either the numerical model or the full-scale prototype structure. The primary objective of the experimental program was to qualitatively investigate the influence of different earthquake records and soil classes on structural behavior under controlled laboratory conditions. Similar to the numerical analyses, the effects of soil-class variation on structural response were also evaluated in the experimental environment, and the obtained findings were interpreted comparatively. Therefore, the experimental results should be considered as supportive observations highlighting the relative influence of different soil conditions on structural behavior rather than as a direct numerical–experimental validation framework.



Figure 3. Experimental setup and sensor locations: (a) experimental setup, (b) placement of accelerometers, and (c) placement of the LVDT sensor

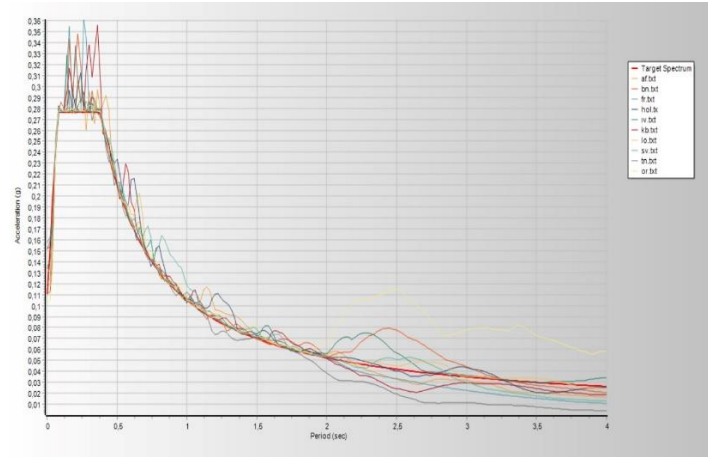
In the current study, eleven actual earthquake records characterized by different properties have been used in order to analyze the effect of earthquakes on structures in a more realistic manner. These earthquake records have been selected based on their properties related to magnitude, frequency content, and other factors, and have been used as inputs in the analysis. The names of the earthquake events, dates, stations for recording, and PGA of earthquake records used in the study have been listed in Table 4 below.

The selected earthquake records were scaled using SeismoMatch software based on the algorithm developed by Al Atik and Abrahamson [24]. According to the simple scaling procedure defined in TBEC 2018, spectral compatibility should be evaluated within the period range of $0.2T_p$ – $1.5T_p$. Considering the first natural vibration period of the investigated structure ($T_p = 0.582$ s), the corresponding period range was approximately 0.116–0.873 s. However, in order to evaluate spectral compatibility over a broader range and better represent the dynamic characteristics of the selected records, the scaling assessment was performed within the period interval of 0–2 s. It should also be noted that near-fault pulse effects were not considered in the present study.

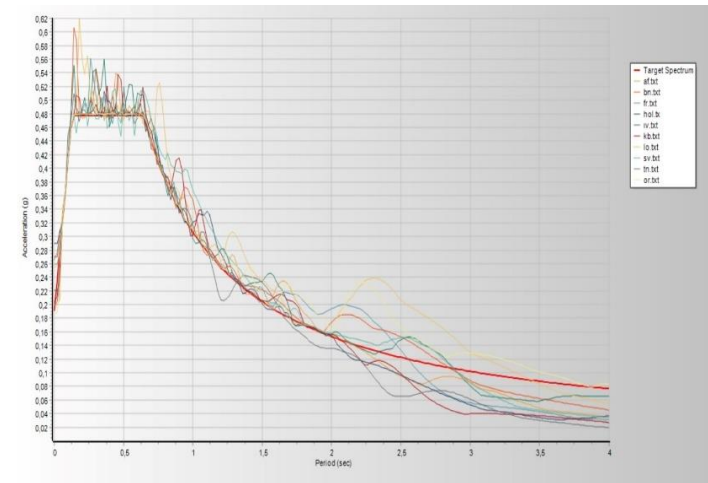
Table 4. Parameters of the Earthquake Records Used in the Analyses

No	Earthquake	Date	Station	Fault Mechanism	PGA (g)	Mw
1	Afyon	2002	Afyon Merkez	Normal	0.115	6.5
2	Bingöl	2003	Bingöl Merkez	Strike-Slip	0.511	6.4
3	Friuli	1976	Tolmezzo	Reverse	0.351	6.5
4	Hollister	1974	Hollister City Hall	Strike-Slip	0.297	5.2
5	Imperial Valley	1979	El Centro Array	Strike-Slip	0.313	6.5
6	Kobe	1995	Kobe JMA	Strike-Slip	0.908	7.2
7	Loma Prieta	1989	Corralitos	Reverse-Oblique	0.550	6.9
8	Northridge	1994	Sylmar County Hospital	Reverse	0.843	6.7
9	Orta	2000	Çankırı Orta	Strike-Slip	0.242	6.0
10	Sivrice	2020	Sivrice	Strike-Slip	0.298	6.8
11	Trinidad	1980	Trinidad Station	Strike-Slip	0.218	7.2

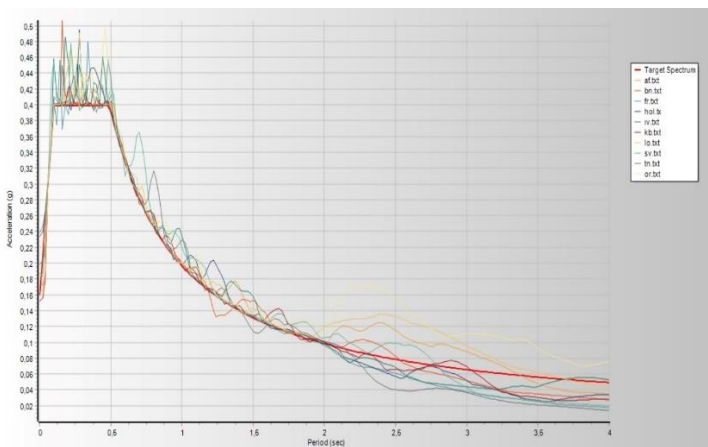
Figures 4 present the spectral matching results obtained for the ZB, ZC, ZD, and ZE soil classes considered in this study. The selected earthquake records were scaled using SeismoMatch software based on the spectral matching algorithm proposed by Al Atik and Abrahamson. The target spectra were generated according to the provisions of TBEC 2018 for the corresponding soil classes. As can be seen from the figures, the response spectra of the scaled earthquake records generally exhibit good agreement with the target spectrum within the period range of interest. Although local deviations are observed at some periods, the overall spectral compatibility is considered satisfactory for the purposes of time-history analyses. The results demonstrate that the adopted scaling procedure successfully adjusted the selected ground-motion records to represent the seismic characteristics of the investigated soil classes. Near-fault pulse effects were not considered in the spectral matching procedure.



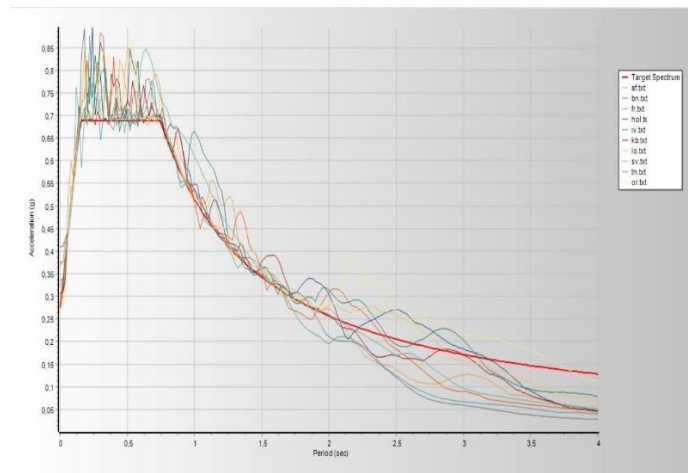
(a)



(b)



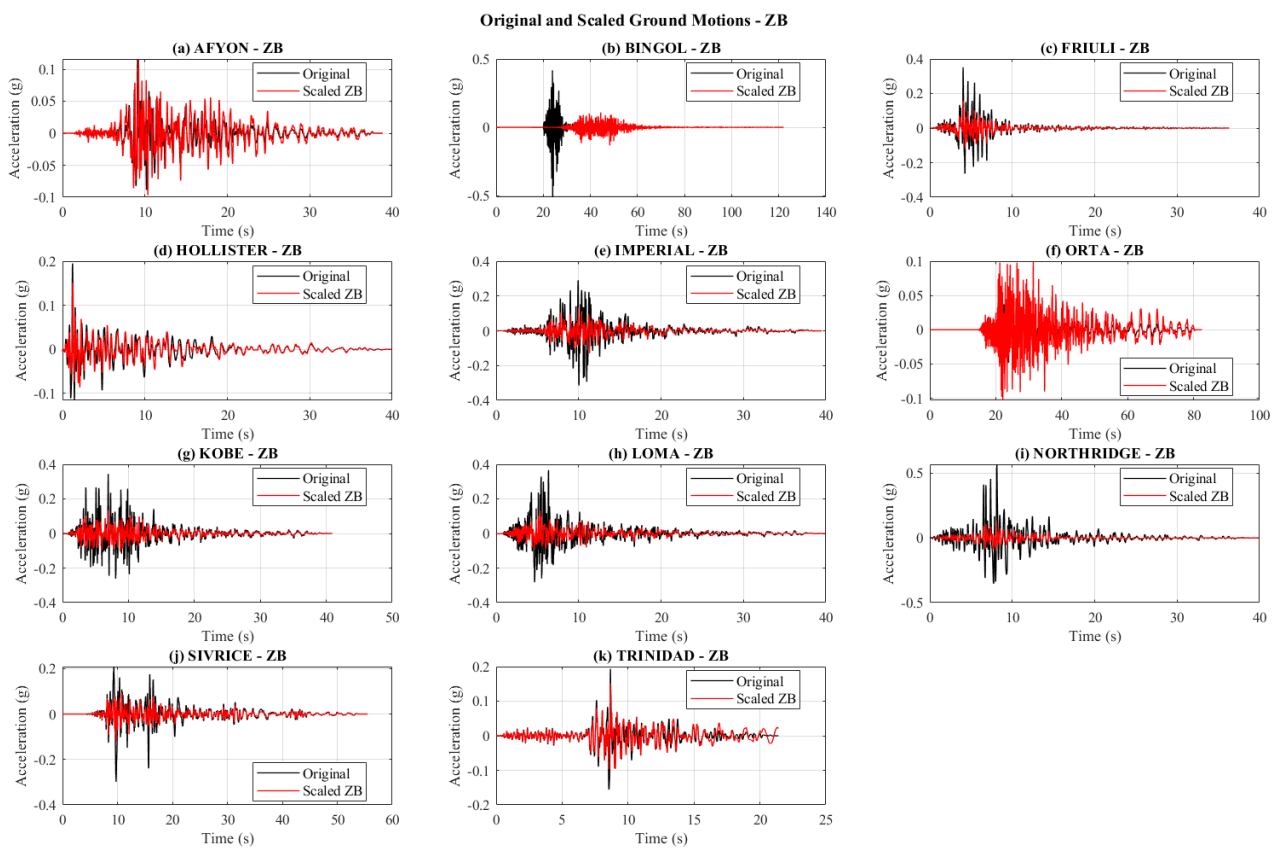
(c)



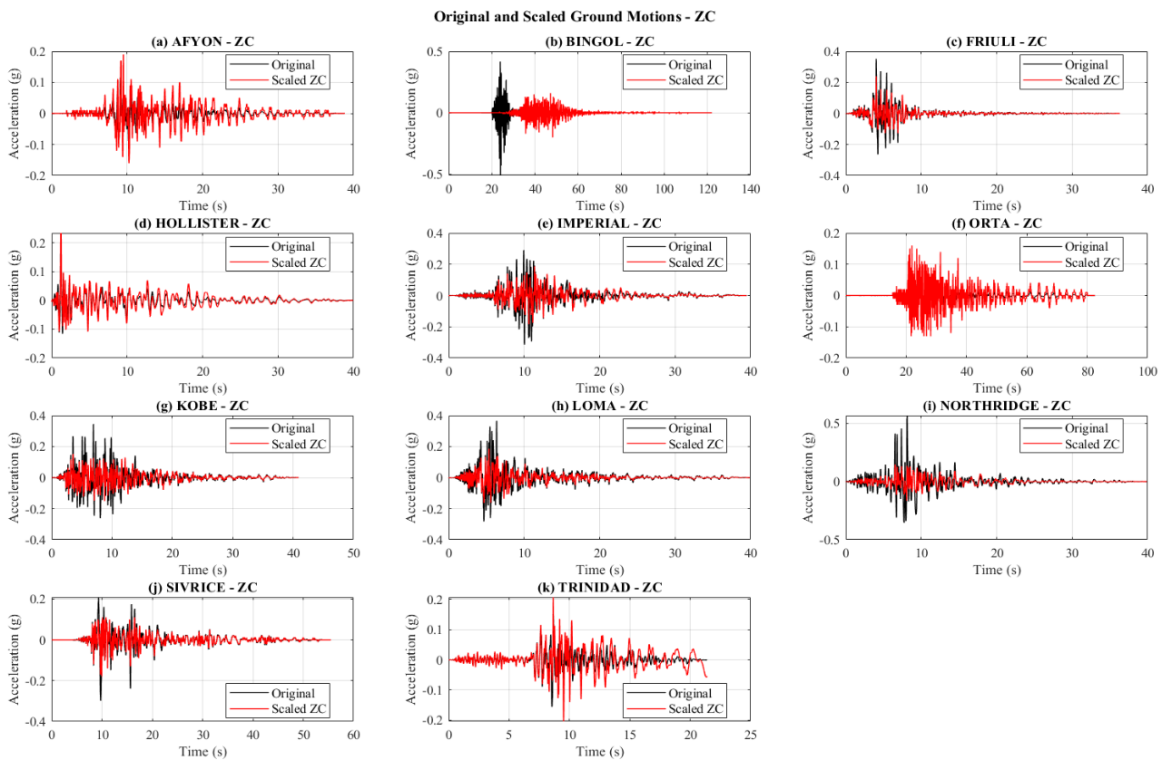
(d)

Figure 4. Comparison of the target spectrum and the spectra of the scaled earthquake records for the Eskişehir site under different soil classes: (a) ZB, (b) ZC, (c) ZD, and (d) ZE

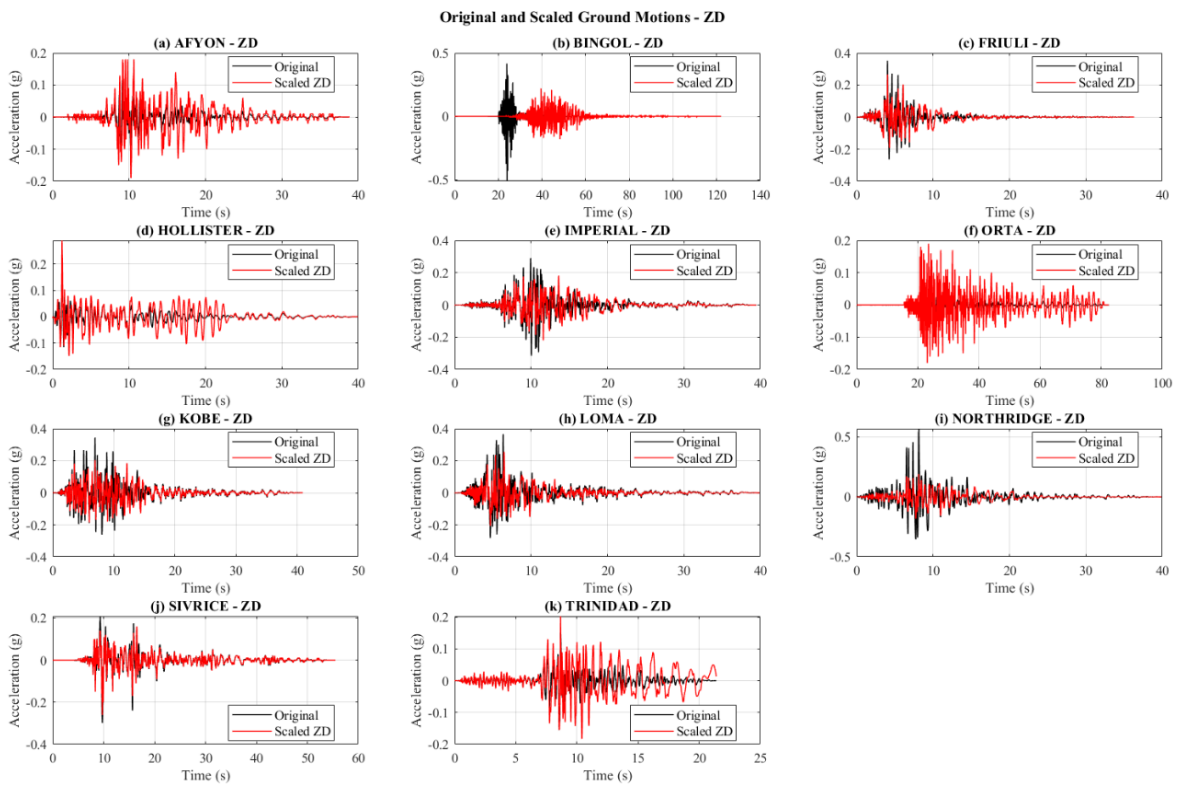
Figure 5 depicts the scaled and unscaled versions of the earthquake records that have been utilized for this analysis. In the current study, the earthquake records have been scaled based on the earthquake parameters of the region of interest as well as the properties of the structure. Scaling the earthquake records was essential to achieve compatibility between the earthquake records and the target response spectrum. As a result, it would be possible to evaluate the dynamic behavior of the structure under various seismic loadings in a more realistic manner.



(a)



(b)



(c)

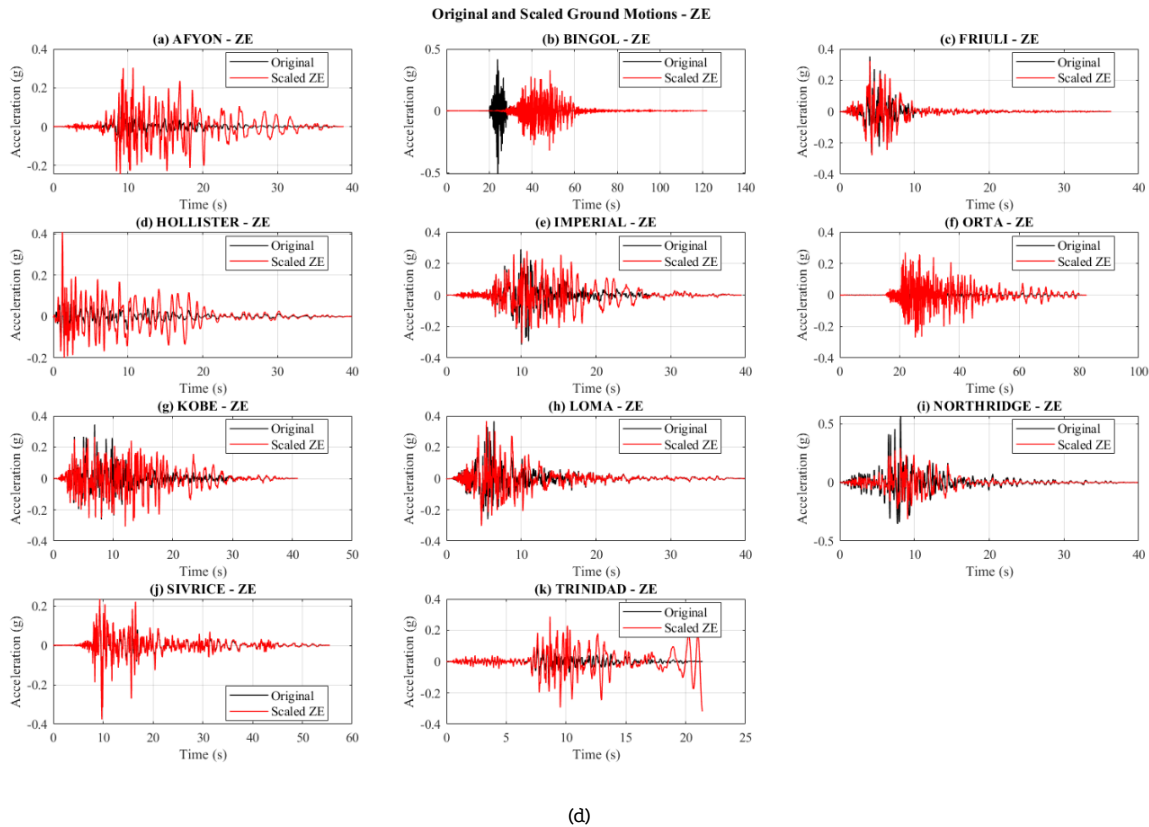


Figure 5. Scaled and unscaled acceleration-time histories of selected earthquake records for different soil classes: (a) ZB soil class; (b) ZC soil class; (c) ZD soil class; (d) ZE soil class

2.4. Structural Steel Quantity Evaluation

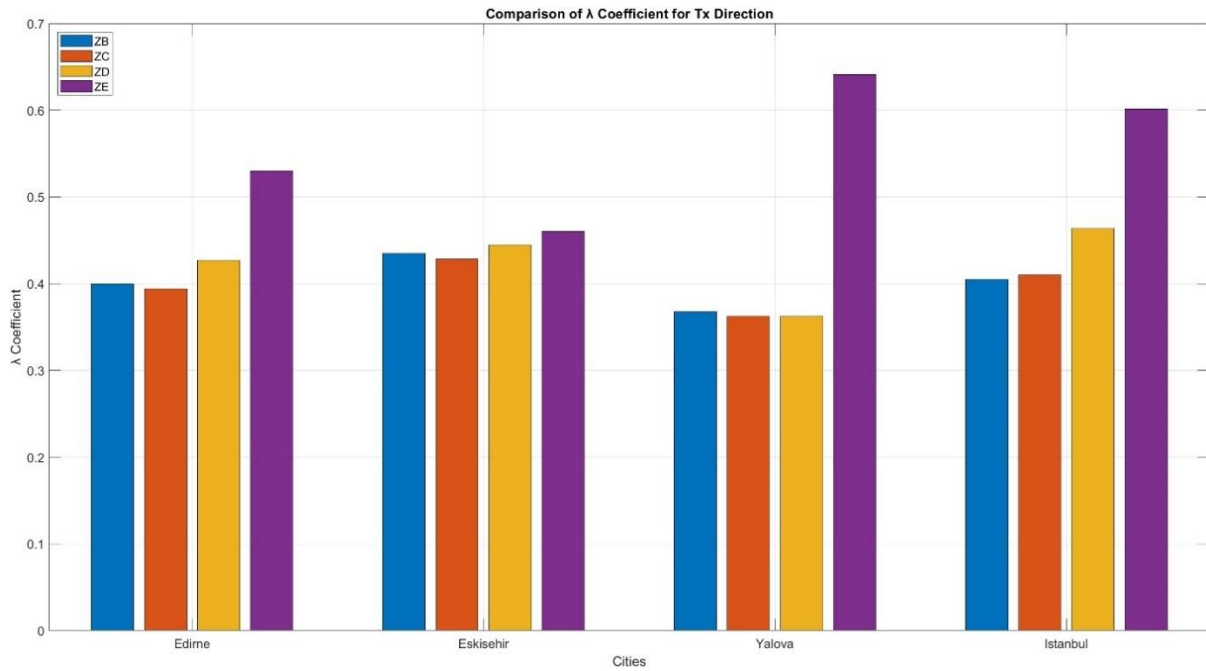
In this study, an assessment of structural steel quantities was conducted to evaluate the effects of different soil classes on steel demand. Instead of direct financial calculations, the total amount of structural steel used in the structural system was considered as the basis for the cost evaluation. This approach aimed to comparatively demonstrate the influence of different soil conditions on structural steel demand. Within this scope, the total structural steel quantities were determined using the cross-sectional properties obtained from the analyses performed for each soil class. The steel tonnages were calculated by considering the section properties and lengths of the structural members and were evaluated separately for each soil class. By comparing the obtained structural steel quantities, the effects of soil classes on structural steel demand were analyzed. Therefore, the presented results should be interpreted as a comparative assessment of structural steel quantity rather than a complete construction cost evaluation.

3. Numerical analyses results

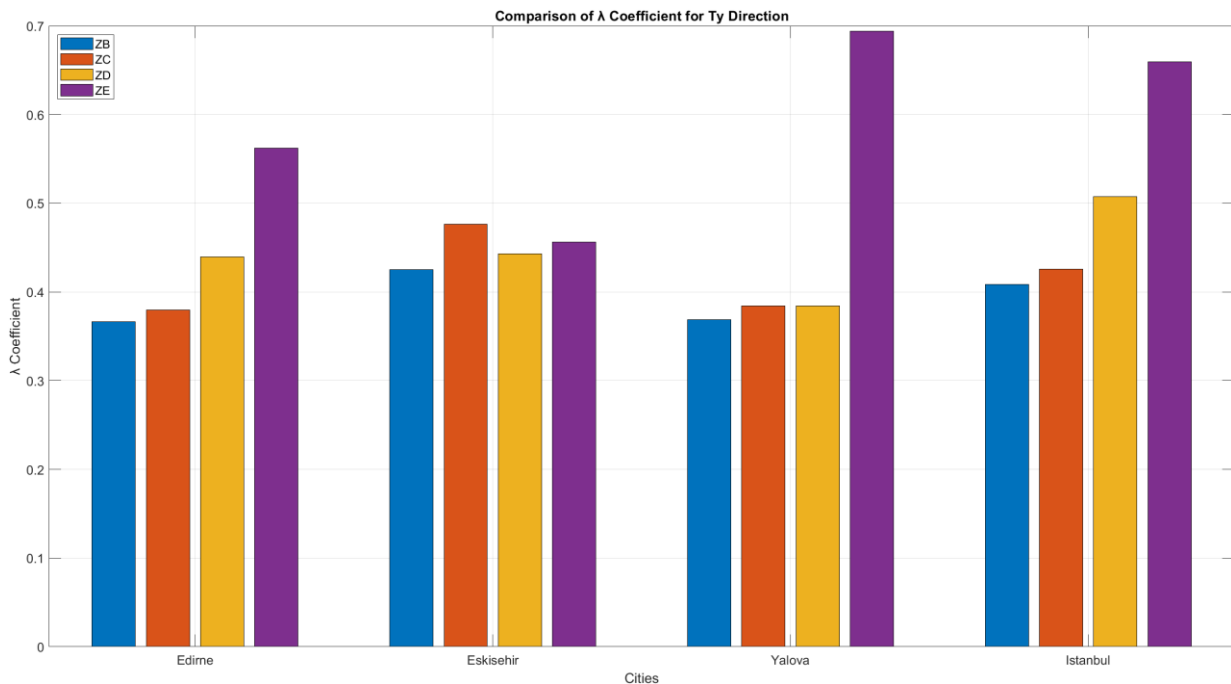
The current section examines the seismic response of the steel industrial structure depending on soil classes using numerical and experimental analysis data. Firstly, the structural behavior parameters were studied as per TBEC 2018 [6]. Thereafter, the responses were analyzed based on time history analyses and shaking table tests. Moreover, the period of vibration of the building was also considered through frequency analyses and comparing the experimental data with the natural period of vibration obtained numerically. Lastly, the impact of soil class on structural steel quantities was assessed based on the calculated steel tonnages.

3.1. Structural performance evaluation

λ Coefficient (which refers to the second-order effect), is considered an important parameter for studying stability behavior under seismic loadings. According to TBEC 2018, the λ coefficient is the indicator of the interaction between story drift and stability, and this value is used to determine whether there is structural safety with respect to second-order effects. Accordingly, the calculated λ coefficients for different soil classes were examined in the Tx and Ty directions, and the findings are illustrated in Figure 6a and Figure 6b. As seen in Figure 6a and Figure 6b, the λ coefficients increased for soft soil classes (ZD and ZE). These changes may be attributed to the high displacements experienced and second-order effects due to low soil stiffness. It should be mentioned that the λ coefficients for ZE soil class are found to be very high for Yalova and Istanbul compared to other soil classes. It is generally assumed that this finding is due to the presence of a high seismic hazard level coupled with soft soil. All calculated λ values stayed under the limit values defined by TBEC 2018, and this means that the structural system has a stable behavior concerning second-order effects. However, an increasing λ value according to decreasing soil stiffness indicates that it is crucial to design a more rigid structure and ensure proper lateral load-resisting system performance in high seismic hazard areas. It is interesting that all results for Tx and Ty directions show similar tendencies, although some cities had slightly higher λ values for Ty directions. Such behavior may be explained by considering the stiffness of the structure system and seismic loading directions. The differences observed in torsional irregularity coefficients are primarily associated with variations in seismic demand resulting from site-dependent design spectra. Since the structural configuration remained unchanged throughout the study, the observed differences reflect the influence of seismic parameters rather than changes in structural geometry or stiffness distribution.



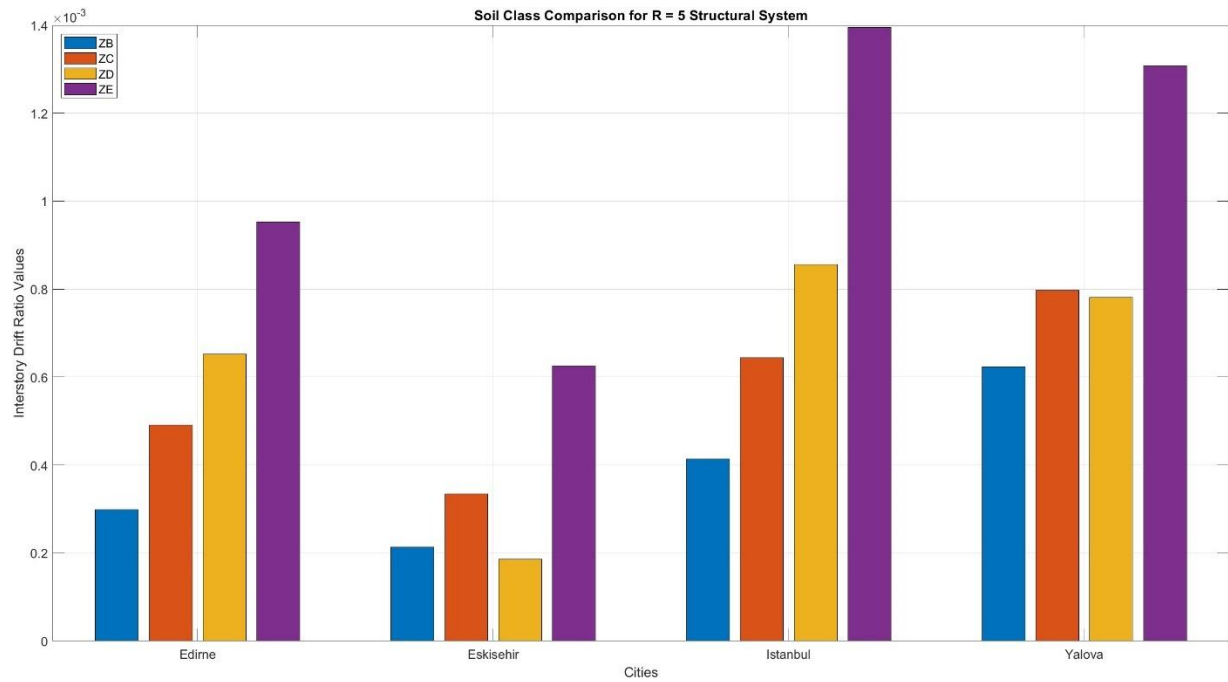
(a)



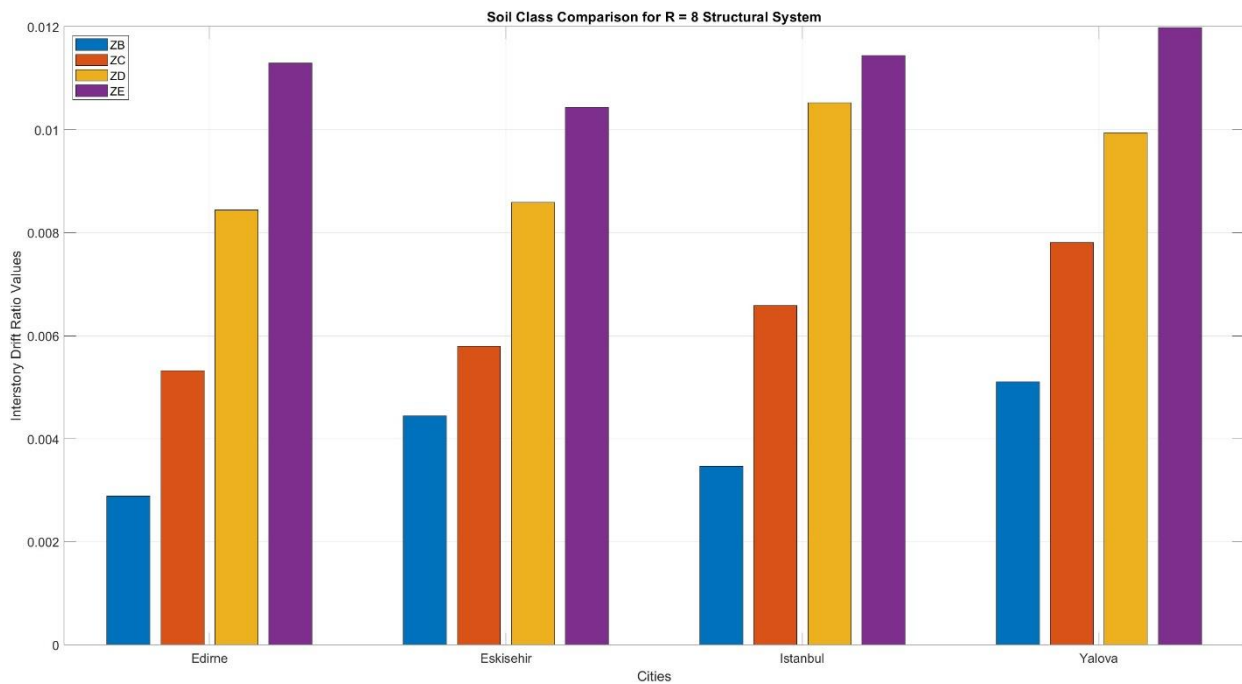
(b)

Figure 6. Comparison of λ Coefficients for Different Soil Classes and Cities: (a) Tx Direction; (b) Ty Direction

Interstory drift ratios form an essential criterion for analyzing the behavior of structures subjected to seismic loads. Interstory drift ratios under different soil class have been examined for structural systems having ductility values of $R = 5$ and $R = 8$ and are presented in Figure 7a and Figure 7b, respectively. From Figures 8a and 8b, it can be seen that the interstory drift ratios increased as the soil condition became poorer. For instance, interstory drift ratios for the $R = 8$ structural systems at Edirne increased from about 0.0029 for ZB soil class to about 0.0113 for ZE soil class. Interstory drift ratios close to 0.012 were also recorded in Istanbul and Yalova with respect to the ZE soil class. Meanwhile, the drift ratios of the $R = 5$ structural systems were smaller compared to those for the $R = 8$ structural systems. TBEC 2018 states that the drift limit for the controlled damage performance level is approximately 0.008 [6]. Based on the results obtained, all drift ratios of the $R = 5$ structural system represented in Figure 7a were less than the above value specified in TBEC 2018. Nonetheless, some of the interstory drift ratios belonging to the $R = 8$ structural systems presented in Figure 7b were found to approach or even exceed the above-mentioned value. However, during the initial analysis stage, some of the interstory drift ratios of the $R = 8$ structural systems presented in Figure 8b were observed to approach and, in some cases, exceed the code-specified limit value. For the models in which the limit value was exceeded, the cross-sections of the structural members were revised by increasing the profile dimensions, and the analyses were repeated. As a result of these revisions, all models were found to satisfy the interstory drift limits specified in TBEC 2018.



(a)



(b)

Figure 7. Comparison of Interstory Drift Ratios for R=5 and R=8 Structural Systems under Different Soil Classes: (a) R=5; (b) R=8

The torsion irregularity factor (η_{bi}) is one of the vital factors that play an important role in the evaluation of the plan stiffness of structures under earthquake loads. According to the provisions of TBEC 2018, torsion irregularity occurs whenever the torsion irregularity factor is greater than 1.2. Under this context, the values of η_{bi} factors for different soil class and cities have been shown in Figure 8.

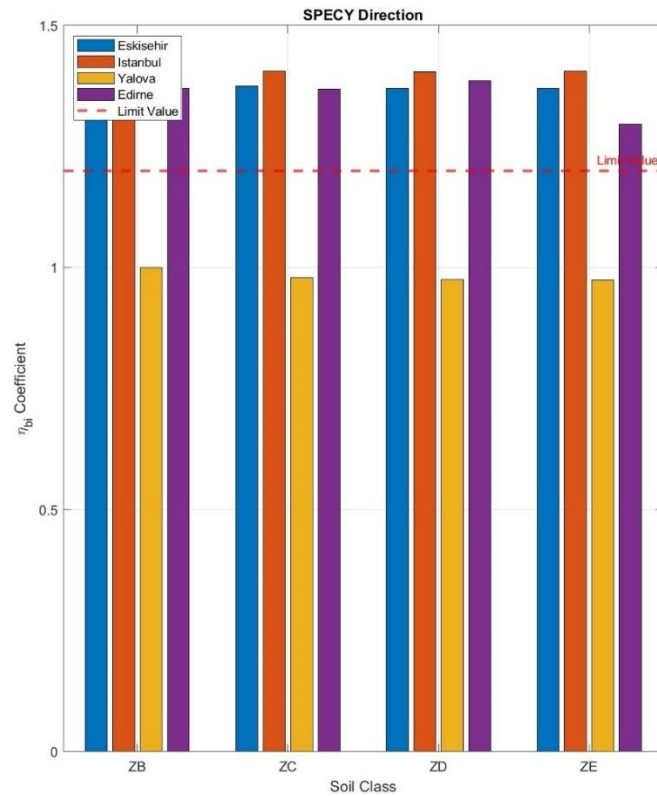


Figure 8. Evaluation of Torsional Irregularity Coefficients for Different Soil Classes

It can be seen from Figure 8 that η_{bi} coefficients for İstanbul, Eskişehir, and Edirne have generally been greater than the limit value in the code of 1.2. That is, for İstanbul, η_{bi} coefficients varied about in the range of 1.39 to 1.40, depending on the soil class. For Eskişehir and Edirne, the η_{bi} coefficients vary about in the range of 1.34 to 1.38. However, for Yalova, η_{bi} coefficients remained below the limit value within the range of about 0.97 to 1.00. It has been determined that there will be an irregular distribution of forces and increased deformations of structures due to the fact that η_{bi} is greater than the limit value of 1.2.

It should be noted that the obtained η_{bi} values do not show a direct correlation with the seismic hazard level of the investigated cities. Although Yalova is characterized by higher seismic demand parameters, larger member sections were required during the design process. The resulting increase in structural stiffness contributed to lower η_{bi} values compared to some of the other investigated cities. Therefore, the observed differences in torsional irregularity should be evaluated considering both seismic demand and the section modifications required to satisfy the code-prescribed interstory drift limitations. In addition, soil class and seismic demand parameters affect the overall seismic response of the structure. For example, inter-story drift ratios and λ coefficients generally increased under ZE soil conditions, while acceleration and displacement demands were more pronounced in cities with higher seismic demand levels.

These observations correspond to those provided by Bruneau et al., who pointed out that ductile behavior was exhibited by steel structural systems during earthquakes [7]. Furthermore, in Riquelme & Herrera (2023) and Monsour et al. (2026), attention was drawn to the fact that deformation increases under soft soil conditions, and the influence of soil properties on seismic response is significant [13-14]. It can be additionally highlighted that, according to the time-history and frequency domain analysis, soft soils play a considerable role in determining the dynamic response and dominant period characteristics of steel structures under seismic loads.

3.2. Dynamic response evaluation under earthquake excitations

Acceleration data recorded at the upper portions of structures undergoing seismic actions are very significant for evaluating the performance of structures. Figure 9a provides the maximum top accelerations found for different earthquake records and soil class. As per results, it becomes apparent that maximum top acceleration values grow significantly with degradation in the quality of soils, the trend becoming more noticeable while comparing ZB and ZE soils. For instance, the maximum top acceleration under the Hollister earthquake record increased from approximately 0.29 g for the ZB soil class to 0.96 g for the ZE soil class, which corresponds to about 230% increment. Likewise, top acceleration value for Loma Prieta earthquake record grows from roughly 0.10g to approximately 0.92g, which is an increment of approximately 820%. This demonstrates the amplification of seismic waves due to soil properties and higher acceleration needs on the part of the upper portions of structures. The similar phenomenon of amplification of accelerations in steel structural frames subjected to dynamic actions is demonstrated by Zamani et al. (2012) [15].

Figure 9b shows maximum base accelerations derived from the structural model used. The results show that maximum base acceleration values also increase with decreasing quality of soils. Specifically, for Hollister earthquake record, base acceleration rises from approximately 0.26g for ZB soil to 0.82g for ZE soil, which is an increment of approximately 215%. For the Loma Prieta earthquake record, the increase is seen from 0.09g to approximately 0.77g base acceleration, which amounts to an increment of about 780%. Furthermore, it can be seen that top acceleration values are larger than base acceleration values, which suggests that seismic forces are being amplified throughout the structural height. Wei (2026) showed that dynamic seismic excitations lead to substantial increases in acceleration needs in steel structures tested on shake tables [16]. Relatedly, Natali et al. (2025) demonstrate that soil properties and features of seismic actions impact acceleration response of steel frames [17].

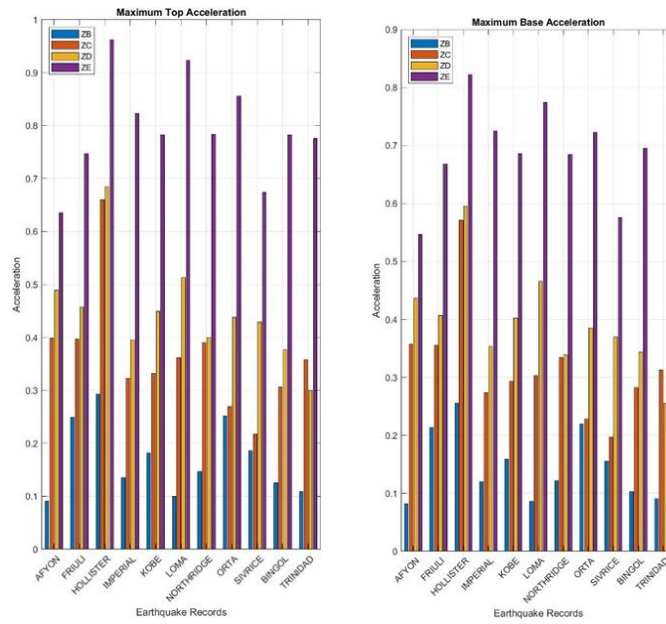


Figure 9. Comparison of Maximum Structural Accelerations under Different Soil Classes and Earthquake Records: (a) Top Accelerations; (b) Base Accelerations

Fig. 10 displays the variation of accelerations from the base to the top of the structure with respect to the Hollister earthquake record. It is evident that acceleration amplification becomes more significant with decreasing soil stiffness. In the case of ZB soil class, differences between base and top acceleration are relatively insignificant. Thus, it could be concluded that structural response to seismic excitation is rather stable under stiff soil conditions. On the contrary, soil classes ZD and ZE demonstrate significant magnifying effects. More importantly, the latter soil class is characterized by the presence of large peak accelerations reaching 1.0 g value, along with high amplitude oscillations and prolonged vibrations of structural components. Therefore, the results indicate that softer soil classes are associated with higher acceleration demands and increased structural response in the investigated cases. As shown in Fig. 10, the highest accelerations both at the base and roof are obtained under the effect of Hollister earthquake record. One of the main factors influencing this effect is the similarity between the frequency content of the Hollister record and natural vibration characteristics of the proposed structural model. Besides, the presence of high acceleration peaks and long-lasting strong ground motion contribute to dynamic amplification of accelerations in the structure. These findings coincide with the research carried out by Çavdar and Güç, stating that effects of soil classes on seismic amplification in steel industrial structures should be considered [18]. In addition, Romaro-Jaren reports that steel structures subjected to strong earthquakes can experience significant acceleration magnification [19]. Based on the presented results, it could be noted that amplification of accelerations between the base and roof becomes more noticeable for softer soils. This statement is corroborated by the research conducted by Eser et al., where it was stated that the dynamic reliability and response characteristics of steel moment-resisting frames are highly dependent on seismic loading intensity and type of soil [20]. Thus, the results indicate that the investigated structural system exhibits increased sensitivity to strong seismic loading and softer soil classes.

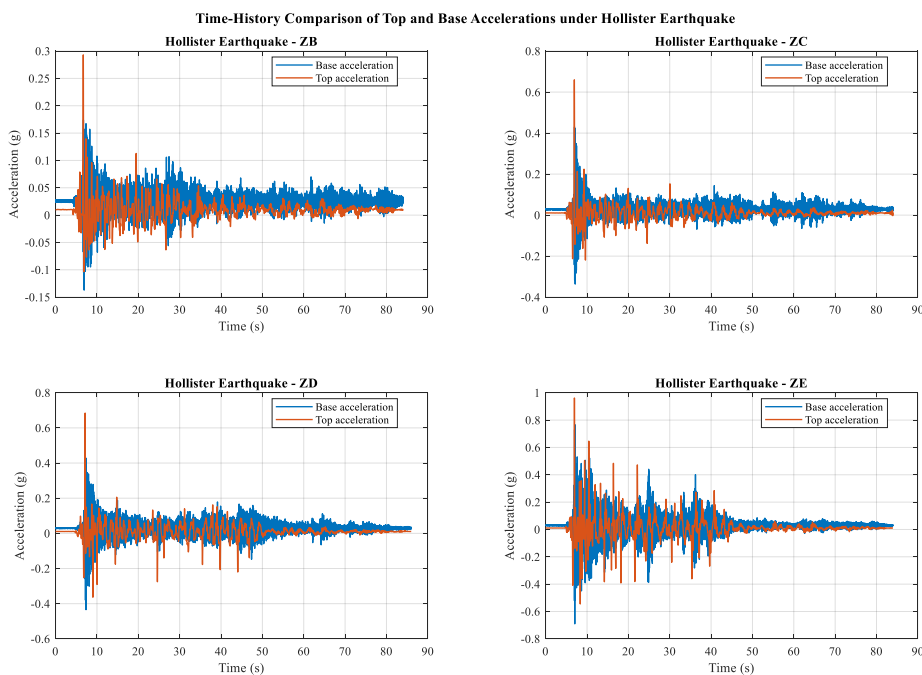


Figure 10. Time-History Comparison of Base-to-Top Acceleration Variations under the Hollister Earthquake Record for Different Soil Classes

Figure 11 shows the results of the Fourier transform in the case of the base and top accelerations for Hollister earthquake data. It should be noted that there is significant change in terms of frequency distribution and the features of the dominant vibrations in the structure under consideration depending on soil classes. For instance, the dominant frequencies of base acceleration for soil classes ZB and ZC are approximately 14.3–14.4 Hz, while for soil class ZD the dominant frequency equals 7.85 Hz. As can be seen from Figure 11, for soil class ZE, the energy distribution of vibrations is relatively broad within the low frequency region, while vibrations amplitudes become higher. Thus, the FFT results suggest a tendency toward increased low-frequency response for the investigated soil classes. As for the FFT results in terms of the dominant frequencies of the top acceleration, the results indicate dominant frequencies predominantly within the 0.67–1.18 Hz range. The FFT results indicate differences in the frequency content and spectral distribution characteristics of the recorded responses for different soil classes. However, no transfer-function, system-identification, or modal-identification analyses were performed in this study. Therefore, the FFT results are presented solely as a comparison of frequency content characteristics and should not be interpreted as direct evidence of resonance or structural modal amplification.

Additionally, it should be stated that these results correspond to the results reported by Sak and Beyen (2019) regarding time–frequency domain analysis that provides critical information for damage formation and dynamic amplification in structures [21]. Furthermore, similar results were provided by Beyen (2017), who highlighted that structural vibration characteristic changes may be used to assess the dynamic behavior and stiffness of structures [22].

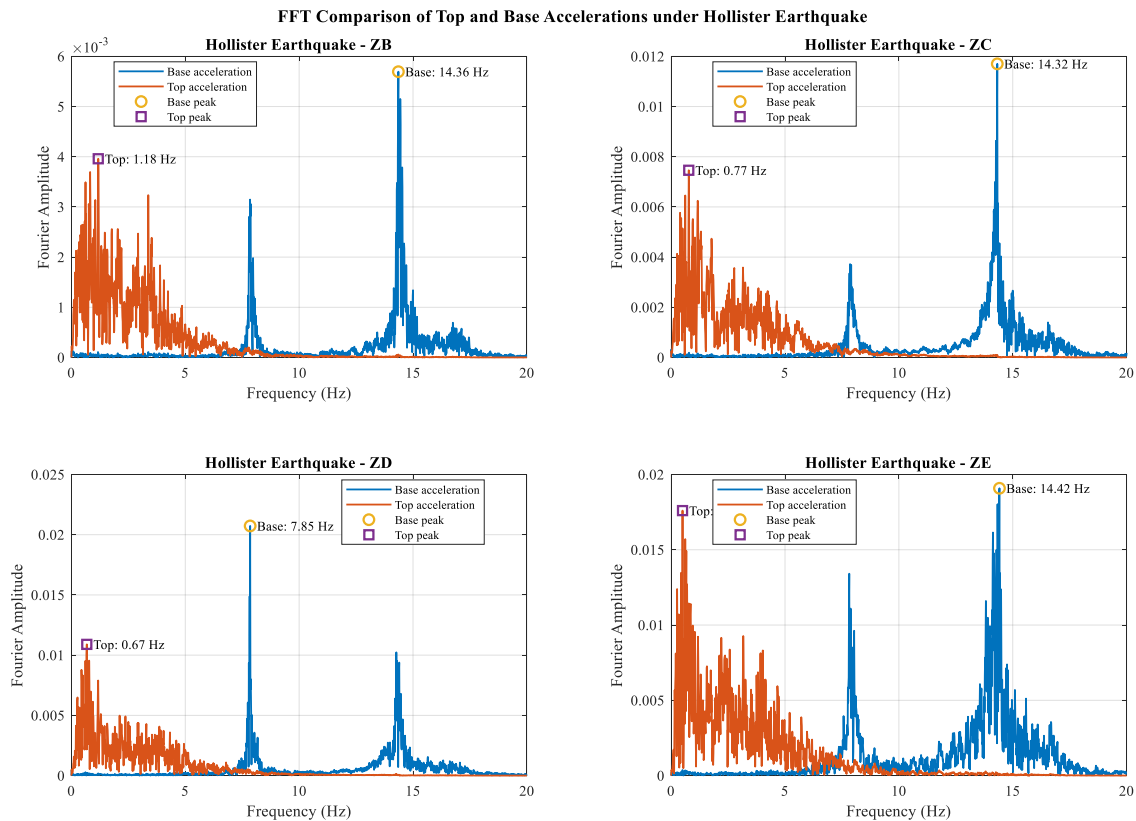


Figure 11. FFT-Based Frequency Domain Comparison of Base and Top Accelerations under the Hollister Earthquake for Different Soil Classes

3.3. Effect of soil classes on structural steel cost

Figure 12 shows the total amount of structural steel used in the steel industrial building structure having similar geometrical characteristics for different types of soils and seismic conditions. It is observed that the use of structural steel depends significantly on the type of soil and seismic factors. Eskişehir requires about 81.653 metric tons of structural steel. The reasons behind this behavior are that the S_s , SDS, and SD1 for Eskişehir are smaller compared to other cities' values. This causes the structural response to be insensitive to the soil changes. Furthermore, the results shown in Section 3.1 regarding λ coefficients and inter-story drift support the relatively less sensitive structural behavior in Eskişehir.

In the case of Edirne, the lowest structural steel quantity corresponds to ZD soil class with a value of about 69.152 tons. Meanwhile, for the ZE soil class, the structural steel requirement is about 93.801 tons. In Yalova, the structural steel quantity increases from about 81.653 tons for the ZB soil class to about 117.936 tons for the ZE soil class. Thus, there is a difference of nearly 44% between these two soil classes. This behavior can be attributed to the need for greater stiffness in structural designs due to high seismic conditions in soft soil.

Along with the results related to the inter-story drift, acceleration amplification, and torsional irregularity described in Section 3.1 and Section 3.2, it can be understood that structural requirements increase considerably under the ZE soil condition. Moreover, larger amounts of structural steels are needed for areas with large values of SDS, SD1, T_a , and T_b . In particular, the structural steel amount becomes largest in case of the Yalova ZE soil condition, in connection with the largest displacement, acceleration amplification, SD1, and T_b values.

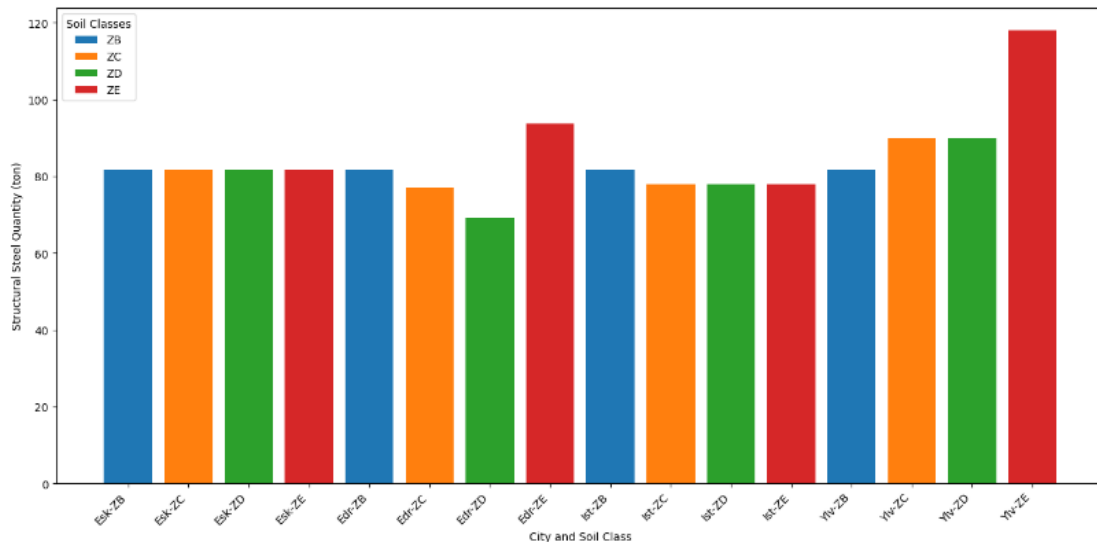


Figure 12. Comparison of Structural Steel Quantities for Different Soil Classes and Seismic Regions

4. Conclusions

This paper sought to determine the effect of varying soil classes and levels of seismic hazard on the seismic performance of steel industrial structures. The equivalent load analysis, time-history analysis, and shake table test were considered in the present study simultaneously. From the results generated in this work, the following conclusions can be drawn.

- The λ coefficient, interstory drift ratio, and torsional irregularity coefficient have been found to increase with worsening soil quality. It was observed that the value of the λ coefficient increased from 0.40 for the ZB soil class to about 0.64 for the ZE soil class, which is a total increase of about 60%.
- The interstory drift ratio was greater for the structural system with $R = 8$ compared to that with $R = 5$. In particular, the maximum interstory drift ratio increased from 0.0029 for the ZB soil class to approximately 0.012 for the ZE soil class, which is an increase of about 310%.
- Results from the time-history analysis and shake table test indicated a significant increase in the top and base acceleration with decreasing soil rigidity. In the case of the Hollister earthquake record, the maximum top acceleration was 0.29 g for the ZB soil class but increased to 0.96 g for the ZE soil class, which implies an increase of 230%. Additionally, the maximum base acceleration changed from 0.26 g to 0.82 g, which corresponds to an increase of 215%.
- Fourier transform analysis showed that softer soils lead to a shift of structural behavior towards low frequencies. The calculated dominant frequency from the base acceleration response dropped from 14.4 Hz for the ZB soil class to 7.85 Hz for the ZD soil class, which means a decrease of about 45%. This result suggests that the structure is more susceptible to resonance effects due to its shift in structural behavior towards low frequencies in softer soils.
- The Hollister earthquake record caused the greatest effect of dynamic amplification because of its dominant frequency spectrum and high acceleration. In particular, the base-to-roof acceleration amplification effect was considerably enhanced when subjected to the ZE soil class.
- The assessment of steel quantities revealed that steel consumption increases significantly in areas of high seismic activity and soil softness. For instance, the structural steel requirement for Yalova increased from 81.653 tons for the ZB soil class to about 117.936 tons for the ZE soil class, which is an increase of 44%.
- Overall, it is evident from the results obtained in the current study that soil classes and seismic factors affect the dynamic response, resonant behavior, amplification, and steel requirement of steel industrial buildings.
- In this study, the cost assessment was performed considering only the quantities of the superstructure steel members, whereas foundation design and connection details were excluded from the scope of the analysis. It is expected that changes in soil class would also considerably affect the material quantities and associated costs related to foundation systems and structural connection details. Hence, future studies should focus on conducting a comprehensive cost analysis that includes both foundation design and connection detailing.

5. Limitations

The present study has some limitations. The shake table tests were conducted for qualitative evaluation purposes and did not employ complete similitude relationships. In addition, explicit soil-structure interaction effects, foundation flexibility, and detailed connection behavior were not considered. The cost assessment was based solely on structural steel quantity and did not include foundation, fabrication, erection, or connection costs.

Furthermore, the shake table tests were used to provide qualitative support for the numerical findings. A detailed model calibration and quantitative experimental-numerical validation were beyond the scope of the present study.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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