Research on Engineering Structures & Materials
www.jresm.org
Research Group

*Research Article*

# Impact of seismic frequency content and pulse-like ground motions on the nonlinear response of RC high-rise buildings including soil-structure interaction

Denise-Penelope N. Kontoni [*,1,2,a], Ahmed Abdelraheem Farghaly [3,b],
Mohamed Atef Mohamed [3,c]

[1]*Dept. of Civil Eng., School of Engineering, University of the Peloponnese, GR-26334 Patras, Greece*
[2]*School of Science and Technology, Hellenic Open University, GR-26335 Patras, Greece*
[3]*Dept. of Civil and Architectural Constructions, Faculty of Technology and Education, Sohag University, Sohag 82524, Egypt*

**Article Info**

***Article History:***

Received 19 Mar 2026

Accepted 21 June 2026

***Keywords:***

Near-fault ground motions;
Pulse-like ground motions;
Frequency content;
Nonlinear time-history analysis;
Soil-structure Interaction;
High-rise buildings;
Reinforced concrete;
Seismic performance

**Abstract**

This study presents a numerical investigation into the sensitivity of a reinforced concrete (RC) high-rise moment-resisting frame building to key ground-motion characteristics, namely frequency content and the presence of forward-directivity pulse-like ground motions. A nonlinear finite-element model of a 15-story RC building incorporating soil-structure interaction (SSI) effects is subjected to five different earthquake ground-motion records, each characterized by distinct frequency content, peak ground acceleration, and waveform characteristics. The selected records are scaled to a consistent intensity level to isolate the effects of different wave shapes. Engineering demand parameters (EDPs), including lateral displacements, base shear, and base moments, are evaluated. The results demonstrate that variations in wave shape and frequency content significantly influence the structural response, leading to amplified lateral displacements, base shear, and base moments. Pulse-like ground motions can produce higher response demands than ordinary ground motions and result in notable lateral drift demands, highlighting the importance of explicitly considering pulse-like ground motions in seismic performance assessment. Moreover, low-frequency ground motions consistently lead to amplified responses in the upper stories. These findings underscore the necessity of explicitly considering pulse-like ground motions in the performance-based seismic assessment of high-rise buildings located in near-fault regions.

## 1. Introduction

Earthquake ground motions affect high-rise buildings (HRBs) primarily through long-period, low-frequency (slow-shaking) motions, which induce significant swaying and lateral displacements, leading to increased interstory drifts and potentially severe or catastrophic structural damage. In contrast, short-duration, high-frequency waves cause stronger shaking in low-rise buildings. HRBs are particularly vulnerable to prolonged low-frequency ground motions, which can cause skyscrapers—especially super high-rise buildings—to exceed their design capacity. The extent of damage is further influenced by factors such as building height, foundation conditions, and soil-structure and structure-structure interactions. Overall, taller buildings are more affected by long-period ground motions, whereas shorter buildings experience greater effects from high-frequency earthquake waves. Conventional seismic design is largely based on elastic response spectra, which reduce complex earthquake ground motions to peak amplitude-frequency representations.

---

[*]Corresponding author: kontoni@uop.gr; kontoni.denise@ac.eap.gr
[a]orcid.org/0000-0003-4844-1094; [b]orcid.org/0000-0002-1602-7748; [c]orcid.org/0009-0008-3887-9790
DOI: http://dx.doi.org/10.17515/resm2026-1576st0319rs

Although efficient for design applications, this simplification masks essential time-domain effects, including the concentration of seismic energy into a small number of large-amplitude cycles (pulses) and the cumulative impact of long-duration shaking. These characteristics are critical in driving structures into the nonlinear response regime, governing damage accumulation, and ultimately controlling collapse potential.

The influence of ground deposits on bedrock motions depends on seismological factors, geological conditions, site-specific geotechnical properties, and geometric characteristics of the site. Comprehensive reviews of local site effects can be found elsewhere (Aki [1]; Somerville [2]). Romo et al. [3] investigated the factors influencing foundation behavior under seismic loading, addressing key aspects such as seismic load characterization, dynamic soil properties, field and laboratory testing techniques, geo-seismic instrumentation of prototype structures, seismic stability of foundations, and the application of artificial intelligence methods. Their findings underscore the importance of accurately capturing soil behavior and soil–foundation interaction in evaluating the seismic response of structures. Mavroeidis and Papageorgiou [4] analyzed a large set of recorded near-field ground motions and developed a procedure for generating realistic synthetic ground motions suitable for engineering analysis and design. Their approach was applied to evaluate the response of structural models subjected to near-source seismic excitations, demonstrating how structural response varies with model input parameters and, ultimately, with earthquake magnitude. Their work demonstrated that pulse-like near-fault motions may induce significantly amplified structural response due to concentrated energy input over a limited number of loading cycles.

Baker [5] developed a method for quantitatively identifying velocity pulses in near-fault ground motions and compared it with other predictor variables, indicating that ground motions exhibiting near-fault directivity effects can be identified fairly consistently, and concluded that the classifications obtained are useful for determining the probability of observing a pulse as a function of earthquake magnitude, distance, source-site geometry, etc. Tothong and Cornell [6] investigated the effects of pulse-like ground motions on structural response and showed that the response depends strongly on the ratio $T_p/T_1$, where $T_p$ is the pulse period and $T_1$ is the fundamental structural period. They also demonstrated that scaling records using advanced intensity measures provides an efficient and robust approach for analyzing structures subjected to pulse-like ground motions. Over a wide range of fundamental periods ($T_1$), the top-floor displacement varies only slightly and is largely insensitive to changes in the beam-to-column stiffness ratio. For very long-period systems, the top-floor displacement approaches the ground displacement, as the floor masses of such systems remain nearly stationary while the ground motion occurs beneath them (Chopra [7]).

Wang and Zhang [8] studied a 3D high-rise building with a pile-raft foundation and found that soil-structure-structure interaction (SSSI) effects are significant under harmonic excitation at frequencies of 1.0–5.0 Hz, with influence coefficients reaching several tens of percent. Under seismic excitation, SSSI effects are generally limited to within ±10%, although foundation sway may increase by up to 26%. The interaction effects are maximized when the excitation direction is perpendicular to the structural layout. Jia et al. [9] investigated the seismic performance of high-rise buildings with podium structures and found that horizontal displacements under moderate earthquakes are small. However, with increasing seismic intensity, the applicability of the structural scheme must be reassessed, and structural details require strengthening and enhancement. Kato and Wang [10] reported that amplification effects associated with site–city interaction (SCI) can reach up to 150–200% within the short-period range of approximately 0.01–0.3 s in the acceleration response spectra. These amplification effects are also reflected in peak ground acceleration (PGA) patterns and structural response characteristics. Since SCI primarily influences short-period structural responses, while the behavior of tall buildings is generally governed by long-period motions, the overall flexural response of high-rise structures is not significantly altered by SCI. However, the amplification of short-period waves due to SCI can significantly increase the maximum relative story accelerations (MSA). Nearly all floors may experience an additional 1–2 $m/s^2$ of MSA in the y direction, while several floors may experience approximately 1 $m/s^2$ additional acceleration in the x direction. Moreover, increased kinetic energy bands may appear at vertical intervals of approximately 30 m, typically affecting groups of 3–6 floors. Within these regions, the buildings may experience a 10–20% increase in destructive energy demand. This repeating pattern is attributed to higher-mode structural responses induced by increased high-frequency spectral accelerations associated with SCI effects.

Alothman et al. [11] investigated the effect of different earthquake characteristics on the seismic response of high-rise buildings (HRBs). Their findings showed that taller buildings are more sensitive to variations in earthquake parameters. Long-duration earthquakes increased the seismic demands on the structures, while near-fault ground motions produced significant responses even when the earthquake duration was short. Wei et al. [12] applied shaking table tests on an HRB model and investigated the impact of ground fissure sites on the deformation laws of connected structures and concluded that the uneven settlement results in mutual influence between connected structures, leading to an overall tilting effect, with a greater amplitude observed in the hanging wall. When the site is situated farther from ground fissures, the dynamic amplification effect on the structure is significantly reduced, and the influence of ground fissures can cause a more obvious phenomenon of translational-torsional coupling in structures. Salem [13] concluded that low-frequency earthquakes have a greater impact on tall structures; when the natural frequency of a building matches the frequency of ground motion, the building will experience the largest possible displacement and may suffer significant structural damage.

Several studies have demonstrated that SSI significantly affects the seismic performance of RC high-rise buildings and may alter structural response when combined with mitigation techniques such as base isolation, tuned mass dampers, bracings, shear walls, and piled-raft foundation systems (e.g., Kontoni and Farghaly [14]; Farghaly and Kontoni [15]; Kontoni and Farghaly [16]; Farghaly and Kontoni [17]; Kontoni and Farghaly [18]; Kontoni et al. [19]). However, the combined influence of seismic frequency content and pulse-like ground motions on RC high-rise buildings considering SSI effects has not been sufficiently explored.

Although previous studies investigated pulse-like ground motions or soil-structure interaction separately, limited research has examined their combined influence on the nonlinear response of reinforced concrete high-rise buildings under different earthquake records with varying frequency content. Therefore, this study aims to address this gap by analyzing a 15-story RC building subjected to earthquake records with different frequency characteristics while explicitly considering SSI effects, with particular emphasis on the impact of seismic frequency content and pulse-like ground motions on the nonlinear seismic response of the structure. The three-dimensional 15-story RC building was analyzed under five different earthquake records to investigate the influence of variations in earthquake characteristics on the seismic response of the high-rise building (HRB), considering soil-structure interaction (SSI) effects. Lateral displacements in the x and y directions, base shear forces, base bending moments, and base axial force ratios obtained from unmodified (natural) and modified (scaled) earthquake records were used to evaluate the structural performance of the building.

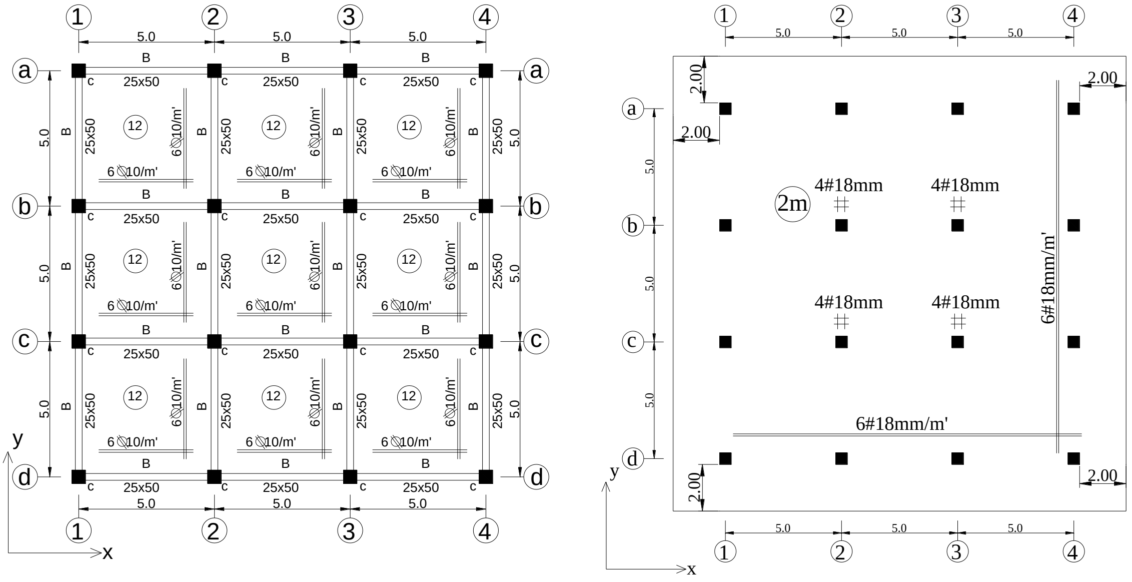
## 2. Prototype Structure

A 15-story building with a 15 m × 15 m footprint and a 3 m story height was studied. The 3D 15-story building with raft foundation was subjected to vertical live load (200 kg/m$^2$) in addition to dead loads (weight of the structural elements and brick walls).

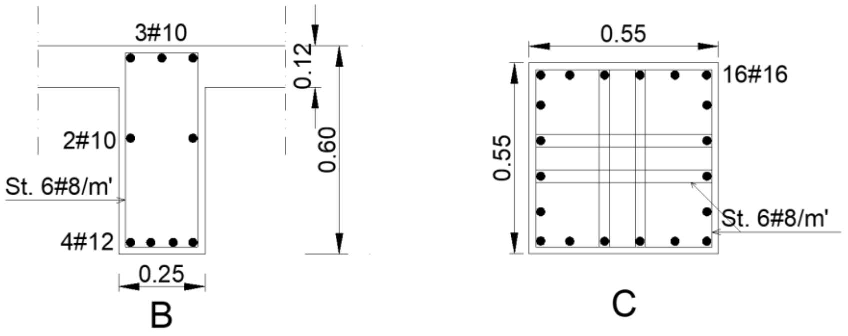
Table 1. Mechanical properties of concrete and reinforcing steel used in the 15-story building

| Material property | | Value |
|---|---|---|
| Concrete | Compressive strength ($f'_c$) (MPa) | 38.1 |
| | Splitting tensile strength ($f'_{ct}$) (MPa) | 3.4 |
| | Modulus of rupture ($f_r$) (MPa) | 3.75 |
| | Modulus of elasticity ($E_c$) (MPa) | 22938.5 |
| Reinforcing steel | Yield stress ($f_y$) (MPa) | 578.18 |
| | Ultimate stress ($f_u$) (MPa) | 655.74 |

Fig. 1 illustrates the structural floor plan, foundation plan, and frame section details. The column cross-sections vary along the building height, with dimensions of 550 mm × 550 mm at the base, gradually reducing to 300 mm × 300 mm at the top. The material properties adopted for the prototype 15-story building are summarized in Table 1. The structure is a representative RC high-rise model based on typical design practices, with realistic dimensions and detailing for nonlinear seismic analysis. The material properties are selected from experimentally validated values and established ranges reported in the literature.



(a) Structural plan of the typical repeated floor (b) Foundation plan with reinforcement details



(c) Beam and column reinforcement details

Fig. 1. Structural layout and reinforcement details of the 15-story building model

## 3. Soil-Structure Interaction (SSI)

Supporting soil properties significantly influence structural seismic response through soil-structure interaction (SSI) effects by modifying foundation flexibility, damping, and the effective dynamic characteristics of the soil-structure system. Softer soils generally increase structural periods and displacement demands, whereas stiffer soils reduce foundation flexibility and may result in greater force transfer into the superstructure.

Medium soil properties (Table 2) support the raft foundation for all earthquakes and the 3D soil element model used in SAP2000 [20] to model the soil under the raft as stiffness (spring) and damping (damper) elements of the soil for vertical and horizontal directions with gaps in x, y and z directions to show the separation between the soil and the raft foundation when subjected to earthquakes, as shown in Fig. 2. Table 3 shows the stiffness (spring) and damping (damper) equations used under raft foundation as Newmark and Rosenblueth [21].

Table 2. Medium Soil properties

| Material | Specific gravity ($G_s$) | Liquid limit (%) | Plastic limit (%) | Plasticity index (%) | Uniformity coefficient | Coefficient of curvature | Dry density (g/cm$^3$) | E (N/mm$^2$) | ν | G (N/mm$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil | 2.65 | 41.5 | 22.6 | 18.9 | 1.46 | 1.09 | 1.75 | 20 | 0.4 | 7.14 |

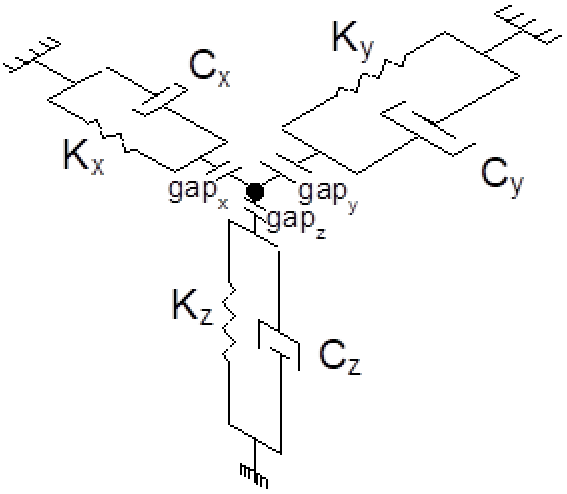


Fig. 2. 3D soil element

Table 3. Stiffness, damping and mass equations for soil model

| Direction | Stiffness | Damping | Mass |
|---|---|---|---|
| Vertical (z direction) | $\frac{4Gr}{1-\nu}$ | $1.79\sqrt{k\rho r^3}$ | $1.50\rho r^3$ |
| Horizontal (x, y direction) | $18.2Gr\frac{(1-\nu)}{(2-\nu)}$ | $1.08\sqrt{k\rho r^3}$ | $0.28\rho r^3$ |

*Note: G = shear modulus, ρ = mass density, ν = Poisson's ratio, r = equivalent foundation radius (Newmark and Rosenblueth [21])*

The adopted spring-damper SSI model was selected because it provides a computationally efficient and widely validated simplified approach for representing foundation flexibility and radiation damping in nonlinear time-history analysis. Compared with full continuum finite-element soil modeling, the adopted method significantly reduces computational demand while adequately capturing the primary soil–foundation interaction mechanisms relevant to the present comparative parametric study.

The adopted SSI model represents the global stiffness and damping contribution of the soil–foundation system through equivalent spring–dashpot elements. Therefore, local nonlinear soil behavior, detailed wave propagation, and complex three-dimensional soil continuum effects are not explicitly modeled. The approach is most suitable for evaluating global structural response trends in nonlinear time-history analyses rather than detailed local soil failure mechanisms.

## 4. Analytical FEM Modeling

The 3D 15-story building with raft foundation was modeled using force-based nonlinear beam-column elements with the cross-sections shown in Fig. 1. The soil properties are summarized in Table 2. A 5% Rayleigh damping model, proportional to the mass and initial stiffness, was adopted. As illustrated in Fig. 3, the three-dimensional 15-story HRB was modeled in SAP2000 [20], with beams and columns represented by frame elements, and slabs and foundations represented by shell elements.

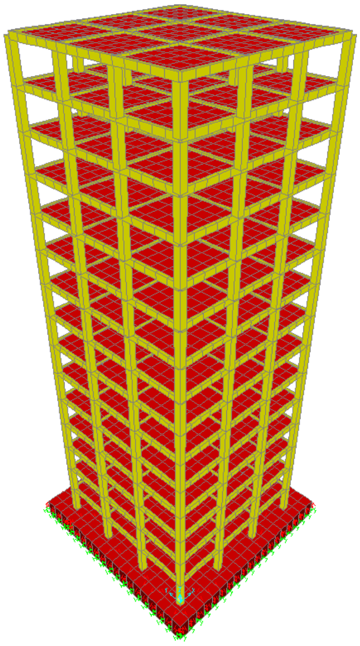


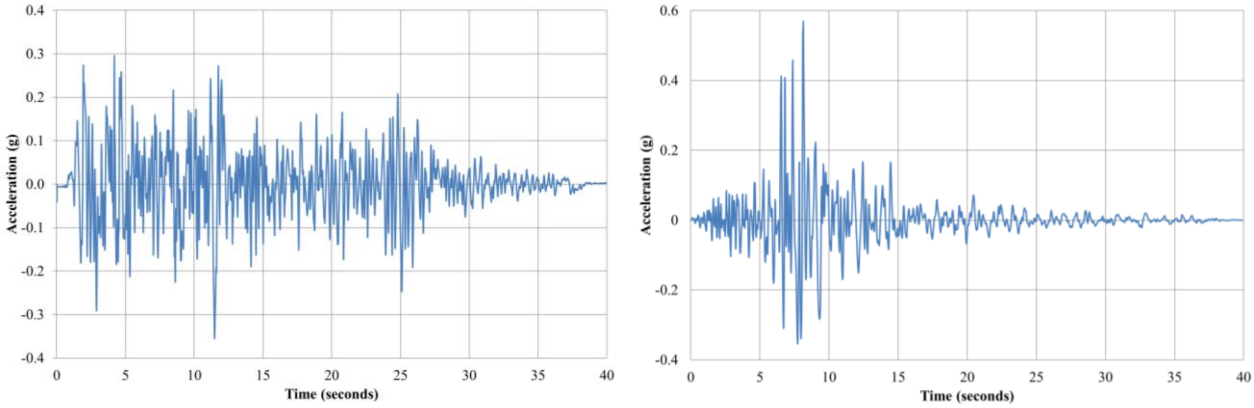
Fig. 3. 3D SAP2000 model of the 15-story building

## 5. Earthquake Specification

The fundamental period of the 3D 15-story building was estimated as $T_1 \approx 2.35$ s using empirical formulas and as $T_1 \approx 2.073$ s using SAP2000 [20]. The dynamic load was applied in the form of earthquake ground motion records obtained from five significant seismic events: the El Centro earthquake with magnitude of 6.9 ($M_w$), Loma Prieta earthquake with magnitude of 6.9 ($M_w$), Northridge earthquake with magnitude 6.7 ($M_w$), Kobe earthquake with magnitude 6.9 ($M_w$), and the Türkiye (Kahramanmaraş) earthquake with magnitude 7.8 ($M_w$). Figure 4 presents the acceleration time histories of the earthquakes used in this study: (i) El Centro (1940) with a PGA of 0.36 g, (ii) Northridge (1994) with a PGA of 0.56 g, (iii) Loma Prieta (1989) with a PGA of 0.364 g, (iv) Kobe (1995) with a PGA of 0.34 g, and (v) Türkiye (Kahramanmaraş, 2023) with a PGA of 1.94 g. Note that different vertical acceleration scales and record durations are used to reflect the actual characteristics and peak ground accelerations of each earthquake. The selected earthquakes include well-established historical records as well as a recent major seismic event in Türkiye.

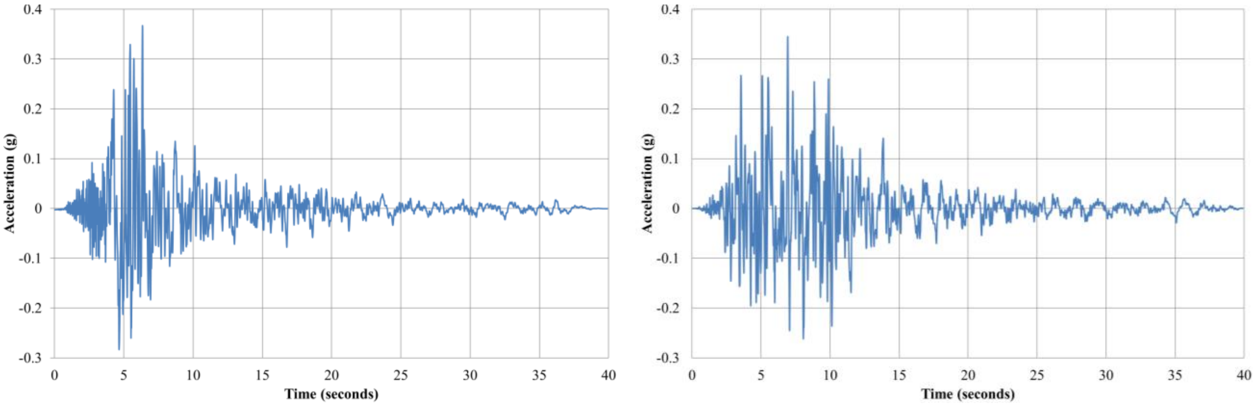
Earthquake ground motion does not have a single fixed amplitude or force; rather, the intensity of shaking at a given location depends on factors such as earthquake magnitude, source-to-site distance, rupture mechanism, and local site conditions. The seismic input data used in structural analyses are typically obtained from instrumental recordings at specific stations, which capture the actual ground motion during an event. Furthermore, the seismic force acting on a structure is not an inherent property of the earthquake itself; rather, it is computed based on the ground acceleration, the mass of the structure, and its dynamic characteristics. Consequently, this study adopts Peak Ground Acceleration (PGA) as a primary intensity measure, as it represents the maximum recorded ground acceleration at a given site and is widely used in engineering practice to estimate seismic forces.

The pulse-like characteristics of the selected near-fault ground motions were identified through inspection of the acceleration time histories, supplemented by comparison with established classification criteria in the literature (e.g., Mavroeidis and Papageorgiou [4]; Baker [5]), which relate large-amplitude velocity pulses to forward-directivity effects in near-fault earthquakes. The selected earthquake records exhibit distinct seismic frequency contents and waveform characteristics. The El Centro (1940) record represents a conventional far-field ground motion without pronounced pulse-like features and is characterized by relatively rich short- to moderate-period components. In contrast, the Northridge (1994), Loma Prieta (1989), Kobe (1995), and Türkiye (2023) records exhibit pulse-like characteristics commonly associated with near-fault directivity effects. Among these, the Türkiye (2023) record exhibits particularly pronounced pulse-like features, indicating the presence of strong directivity effects; however, its spectral content is still primarily dominated by relatively short-period components.



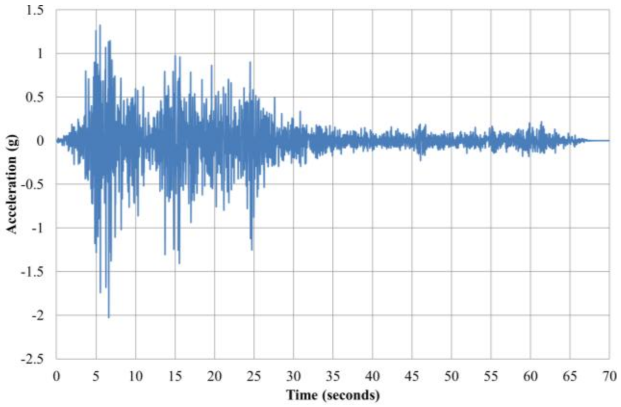
(a) El Centro

(b) Northridge



(c) Loma Prieta

(d) Kobe



(e) Türkiye (Kahramanmaraş)

Fig. 4. Acceleration time-history records of the selected earthquake ground motions used in the dynamic analysis: (a) El Centro (1940), (b) Northridge (1994), (c) Loma Prieta (1989), (d) Kobe (1995), and (e) Türkiye (Kahramanmaraş, 2023)

Although only five earthquake records were considered in this study, the objective is not statistical probabilistic assessment but rather comparative parametric evaluation of representative ground motions with different seismic frequency contents, pulse-like characteristics, and intensity levels. The selected record set intentionally includes a broad range of waveform characteristics to enable focused investigation of the influence of frequency content and pulse-like behavior on structural response.

Spectral analysis of the El Centro (1940) acceleration record indicates a dominant frequency of approximately 2.38 Hz, corresponding to a dominant period of about 0.42 s. The Fourier amplitude spectrum of the El Centro (1940) earthquake shows dominant frequency peaks corresponding to periods between approximately 0.4 s and 0.5 s, indicating that the ground motion is characterized by relatively high-frequency seismic content, typical of far-field earthquake records. Since the dominant ground-motion period is significantly smaller than the fundamental period of the analyzed 15-story building ($T_1 \approx 2.073$ s), the El Centro earthquake is expected to generate lower displacement demands compared with long-period pulse-type ground motions that are closer to the structural period. Nevertheless, the presence of spectral energy extending up to about 1.5–2.0 s suggests that the record still contains components capable of influencing low- to mid-rise buildings.

Spectral analysis of the Northridge (1994) earthquake record indicates a dominant frequency of approximately 1.23 Hz, corresponding to a dominant period of about 0.81 s. The Fourier amplitude spectrum of the Northridge (1994) earthquake shows dominant frequency peaks corresponding to periods between approximately 0.7 s and 0.9 s. This indicates a moderate-frequency ground motion. Since the dominant period of the ground motion is shorter than the fundamental period of the analyzed 15-story building ($T_1 \approx 2.073$ s), resonance effects are not expected to occur. However, the Northridge earthquake is characterized by near-fault pulse-like features, which may still produce significant structural responses and increased lateral displacement demands compared with typical far-field earthquakes.

Spectral analysis of the Loma Prieta (1989) earthquake record indicates a dominant frequency of approximately 0.63 Hz, corresponding to a dominant period of about 1.60 s. The Fourier amplitude spectrum of the Loma Prieta (1989) earthquake shows dominant frequency peaks corresponding to periods between approximately 1.2 s and 2.0 s, indicating the presence of low-frequency (long-period) ground-motion components, which can significantly influence flexible high-rise structures. This relatively long period further confirms that the ground motion contains low-frequency seismic components, which strongly influence flexible structures such as high-rise buildings. Since the dominant period of the ground motion is relatively close to the fundamental period of the analyzed 15-story building ($T_1 \approx 2.073$ s), this earthquake record is expected to generate considerable lateral displacement and drift demands compared with higher-frequency ground motions.

Spectral analysis of the Kobe (1995) earthquake record indicates a dominant frequency of approximately 0.59 Hz, corresponding to a dominant period of about 1.71 s. The Fourier amplitude spectrum of the Kobe (1995) earthquake shows dominant frequency peaks corresponding to periods between approximately 1.6 s and 1.8 s, indicating strong long-period seismic content often associated with near-fault pulse-like ground motions. In the Kobe record, this relatively long period also indicates that the ground motion contains low-frequency seismic components, which are particularly important for flexible structures such as high-rise buildings. Because the dominant ground-motion period is close to the fundamental period of the analyzed 15-story building ($T_1 \approx 2.073$ s), the Kobe earthquake is expected to produce significant lateral displacement and drift demands. In addition, the Kobe record exhibits pulse-like characteristics associated with near-fault ground motions, which may further amplify the structural response.

Spectral analysis of the Türkiye (Kahramanmaraş, 2023) earthquake record indicates a dominant frequency of approximately 6.91 Hz, corresponding to a dominant period of about 0.145 s, which reflects the presence of strong high-frequency ground-motion components. This short dominant period indicates that the ground motion is characterized by high-frequency seismic components. Because the dominant ground-motion period is significantly smaller than the fundamental period of the analyzed 15-story building ($T_1 \approx 2.073$ s), resonance effects are unlikely to occur. Consequently, this earthquake record is expected to produce lower lateral displacement demand compared with long-period ground motions, although higher acceleration responses may occur in the structure.

The frequency characteristics of the selected earthquake records were evaluated using spectral analysis of the acceleration time histories. The Loma Prieta (1989) and Kobe (1995) earthquakes exhibit dominant frequencies of approximately 0.63 Hz and 0.59 Hz, corresponding to dominant periods of about 1.60 s and 1.71 s, respectively, indicating strong low-frequency (long-period) ground-motion content. The Northridge (1994) earthquake shows a dominant frequency of approximately 1.23 Hz (dominant period ≈ 0.81 s), representing moderate-frequency ground motion. In contrast, the El Centro (1940) earthquake is characterized by a higher dominant frequency of approximately 2.38 Hz, corresponding to a shorter dominant period of about 0.42 s, which represents high-frequency seismic waves typically associated with far-field ground motions. Finally, the Türkiye (Kahramanmaraş, 2023) record exhibits dominant high-frequency components with a dominant frequency of approximately 6.9 Hz (dominant period ≈ 0.15 s). Although the Türkiye (2023) record is dominated by high-frequency content, it exhibits a short-duration velocity pulse and is therefore classified as pulse-like. Considering that the fundamental period of the analyzed 15-story building is approximately $T_1 \approx 2.073$ s, earthquake records with longer dominant periods, such as Loma Prieta and Kobe, are expected to produce larger lateral displacement and drift demands, whereas higher-frequency motions such as Türkiye are less likely to resonate with the flexible high-rise structure.

In addition to frequency content, several of the selected earthquakes exhibit pulse-like ground-motion characteristics, which are commonly associated with near-fault directivity effects. Pulse-like ground motions are characterized by a large-amplitude velocity pulse occurring within a short time interval, resulting from the forward rupture propagation toward the recording station. These pulses concentrate a large portion of seismic energy into a small number of cycles, which can significantly increase structural response, particularly in flexible structures such as high-rise buildings. Previous studies have shown that the severity of structural response under pulse-like ground motions depends strongly on the ratio between the pulse period $T_p$ and the fundamental structural period $T_1$. When the pulse period approaches the structural period $\left(T_p/T_1 \approx 1\right)$, resonance-like conditions may occur, resulting in significant amplification of lateral displacements, interstory drifts, and internal forces. Because the fundamental period of the analyzed 15-story building is approximately $T_1 \approx 2.073$ s, earthquake records containing long-period pulse-like components may generate substantially higher seismic demands compared with high-frequency ground motions.

Table 4. Summary of selected earthquake ground-motion characteristics, including dominant period, frequency classification, and pulse-like features

| Earthquake | Year | PGA (g) | Dominant Period (s) | Frequency Type | Pulse-like |
|---|---|---|---|---|---|
| El Centro | 1940 | 0.36 | ≈0.42 | High-frequency | No |
| Loma Prieta | 1989 | 0.364 | ≈1.60 | Low-frequency | Yes |
| Kobe | 1995 | 0.34 | ≈1.71 | Low-frequency | Yes |
| Northridge | 1994 | 0.56 | ≈0.81 | Moderate-frequency | Yes |
| Türkiye | 2023 | 1.94 | ≈0.15 | High-frequency | Yes |

The pulse period $T_p$ is not an intrinsic constant of an earthquake event, but depends on the selected station, component, and pulse-extraction procedure. Therefore, comparisons between structural period $T_1$ and pulse period $T_p$ should be made using the specific ground-motion record adopted in the analysis, rather than assigning a single $T_p$ value to the entire earthquake. The fundamental period of the analyzed 15-story building is approximately $T_1 \approx 2.073$ s. Comparison with the estimated pulse periods of the selected earthquake records shows that the El Centro record represents a non-pulse far-field motion, while the Northridge ($T_p$≈1.1–1.3 s) ground motion exhibits a pulse period smaller than the building period. In contrast, the Loma Prieta ($T_p$≈1.4–1.8 s) and Kobe ($T_p$≈1.4–1.8 s) earthquakes exhibit pulse periods closer to the fundamental period of the structure. The Türkiye (Kahramanmaraş, 2023) earthquake record is dominated by high-frequency components, with an estimated dominant pulse period of approximately $T_p$≈ 1.3–1.5 s, which is shorter than the structural period. (Although the Türkiye record contains high-frequency components, the time history also shows a short-duration velocity pulse associated with near-fault directivity). When the pulse period approaches the structural period ($T_p/T_1 \approx 1$), resonance-like dynamic amplification may occur, leading to increased lateral displacements and drift demands in flexible high-rise structures. Table 4 summarizes the key characteristics of the selected earthquake ground-motion records, including peak ground acceleration (PGA), dominant period, frequency classification, and the presence of pulse-like features.

Figure 5 illustrates the key ground motion parameters adopted in the numerical analysis, providing an overview of the characteristics and specifications of each earthquake record used in this research. As shown in Figure 5, the Türkiye (2023) earthquake exhibits significantly higher acceleration demands compared to the other records, which justifies the higher scaling factors and equivalent acceleration values adopted in the dynamic analysis. To ensure a consistent amplitude level and isolate the influence of wave shape and frequency content, all records were scaled to a common peak ground acceleration (PGA), defined as the mean PGA of the record set. Although peak ground acceleration (PGA) is not the most efficient intensity measure for flexible high-rise structures, it was adopted in this study to provide a consistent amplitude normalization across the selected records, allowing the influence of waveform characteristics and frequency content to be isolated and evaluated independently of overall motion intensity.

To enable a direct comparison of structural response under different seismic frequency contents and pulse characteristics, all selected ground motion records were normalized to a common intensity level. Specifically, each record was linearly scaled so that its peak ground acceleration (PGA) equaled 0.7128 g, which corresponds to the mean PGA of the unscaled ground motion set. By enforcing a uniform PGA level across all records, the influence of overall amplitude is minimized, allowing observed differences in structural response to be primarily attributed to variations in frequency content and pulse-type characteristics rather than differences in record strength. It is acknowledged that PGA is not the most efficient intensity measure for mid- to high-rise structures; however, its use here is limited to comparative evaluation of ground motion characteristics under a fixed amplitude level.

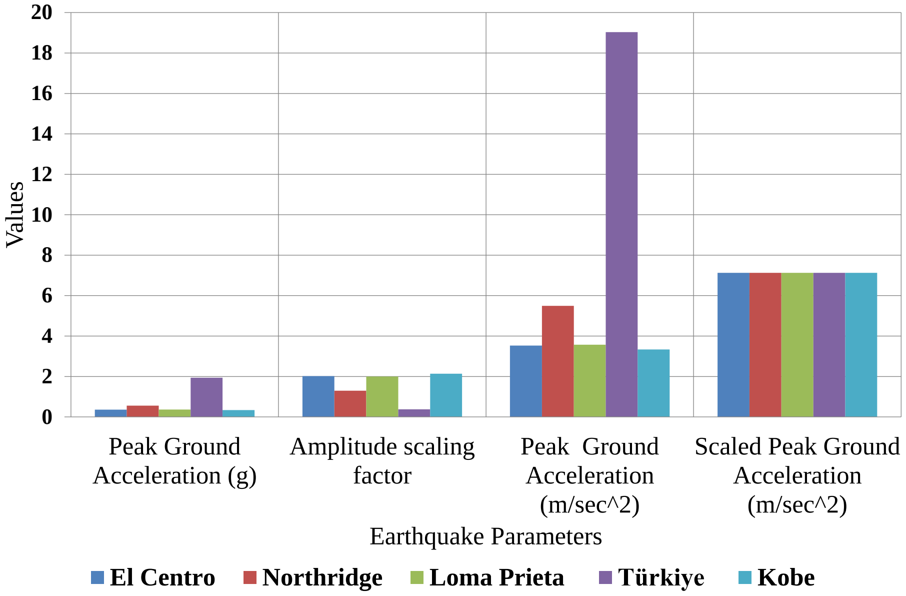


Fig. 5. Comparison of key seismic parameters for the selected earthquake ground motions, including peak ground acceleration, scaling factors, and equivalent acceleration values used in the dynamic analysis

Scaling of the earthquake records to a common PGA level was performed to isolate the influence of waveform characteristics and frequency content from differences in overall motion amplitude. By normalizing the peak acceleration of all records, the observed variations in structural response may be attributed primarily to differences in spectral content, pulse characteristics, and temporal energy distribution rather than differences in absolute seismic intensity. The selected set of earthquake records represents a range of frequency contents, pulse-like characteristics, and intensity levels, enabling a focused investigation of how these parameters influence the nonlinear response of high-rise buildings. The objective of the study is not statistical ground-motion prediction but rather comparative evaluation of structural response under representative earthquake scenarios**.** Therefore, the selected records are not intended for statistical representation but rather for controlled comparison of key ground-motion characteristics. By combining records with different frequency characteristics, waveform shapes, and near-fault pulse effects, the analysis provides insight into how ground-motion properties influence the nonlinear response of high-rise structures when soil-structure interaction is considered.

## 6. Results and Discussion

The 3D 15-story RC building was analyzed using five earthquake records with different specifications and parameters to show the effect of these parameters on the seismic response of the HRB. The results were first evaluated for the original earthquake records and then for modified records in which each ground acceleration was scaled to the same average peak ground acceleration (PGA). Table 5 presents the definitions of all symbols used in the subsequent figures.

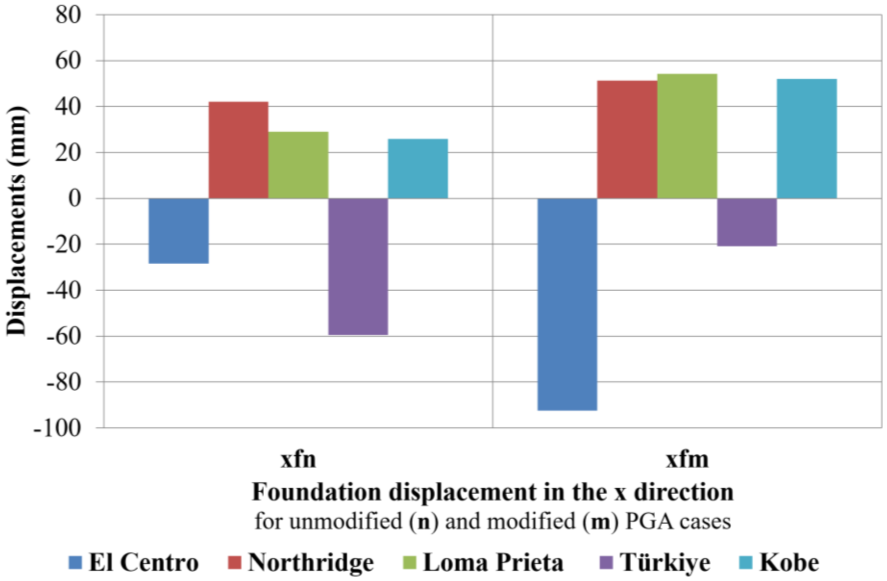
Table 5. Definition of symbols

| Symbol | Definition |
|---|---|
| Q | Base shear. |
| M | Base moment. |
| x | x direction. |
| y | y direction. |
| n | No modification of peak ground acceleration:<br>Analysis using original (not modified) peak ground acceleration. |
| m | Modification of peak ground acceleration to equal peak ground acceleration:<br>Analysis using modified (scaled) PGA, scaled to match the target PGA. |
| t | Top building point: Response at the top of the building. |
| f | Foundation building point: Response at the foundation of the building. |
| N ratio | N ratio = Nm/Nn<br>Ratio of base axial force obtained from modified PGA analysis (Nm) to that from unmodified PGA analysis (Nn). |

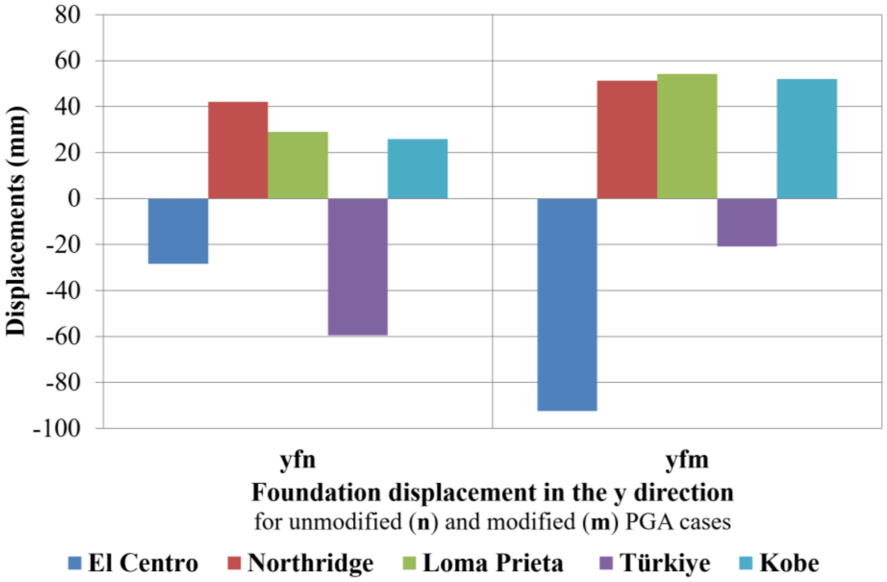
Key response quantities, including lateral displacements, base shear forces, base moments, and axial force ratios, were examined to highlight the differing effects of the selected earthquake records. Figure 6 presents the lateral displacement responses at the foundation level under different earthquake records. Figure 6(a) shows the lateral displacements at the foundation level in the x direction. In the unmodified earthquake records, the maximum displacement is observed for the Türkiye earthquake, while the minimum displacement occurs for the Kobe earthquake. In the modified earthquake cases, in which all records are scaled to the same average PGA, the maximum lateral displacement occurs under the El Centro earthquake, whereas the minimum displacement is obtained for the Türkiye earthquake. Figure 6(b) shows the lateral displacements at the foundation level in the y direction, following the same response trends as those in the x direction.

Figure 7 presents the lateral displacement responses at the top-story level of the building under different earthquake records. Figure 7(a) presents the lateral displacements at the top-story level in the x direction. In the unmodified (natural) earthquake records, the maximum displacement is observed for the Loma Prieta earthquake, while the minimum displacement occurs for the Kobe and El Centro earthquakes. In the modified earthquake cases, in which all records are scaled to the same average PGA, the maximum lateral displacements are obtained for the El Centro and Loma Prieta earthquakes, whereas the minimum displacement occurs for the Türkiye earthquake. Figure 7(b) shows the top-story lateral displacements in the y direction, following the same response trends as those in the x direction.

Although both the Loma Prieta (1989) and Kobe (1995) earthquake records exhibit dominant periods (≈1.60 s and ≈1.71 s, respectively) relatively close to the fundamental period of the analyzed structure ($T_1 \approx 2.073$ s), the resulting displacement demands differ significantly, indicating that structural response is not governed solely by period proximity, but also by waveform shape, pulse amplitude, duration, spectral energy distribution, and temporal concentration of seismic energy. In particular, the Loma Prieta record produces larger displacements due to a broader and more sustained concentration of low-frequency energy, which enhances energy transfer to the flexible high-rise structure.



(a) Lateral displacements at foundation in the x direction.

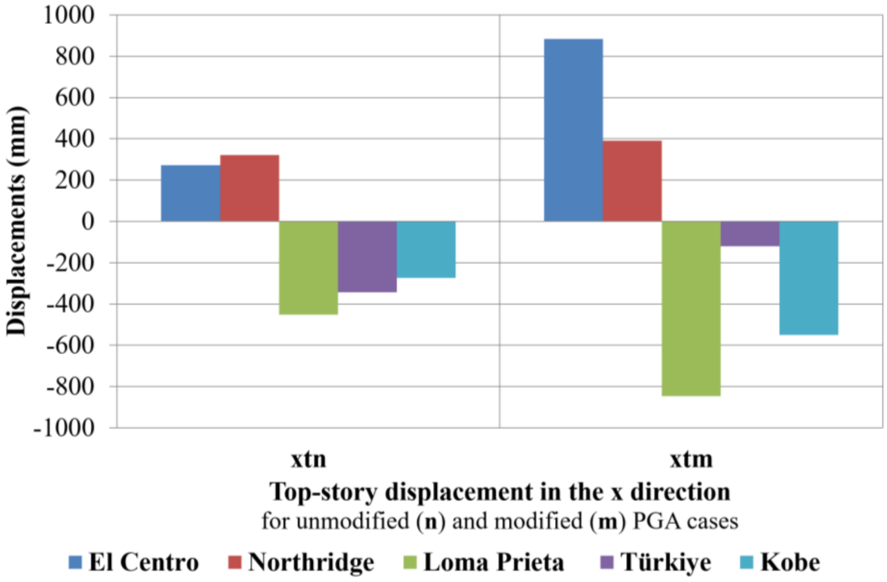


(b) Lateral displacements at foundation in the y direction.

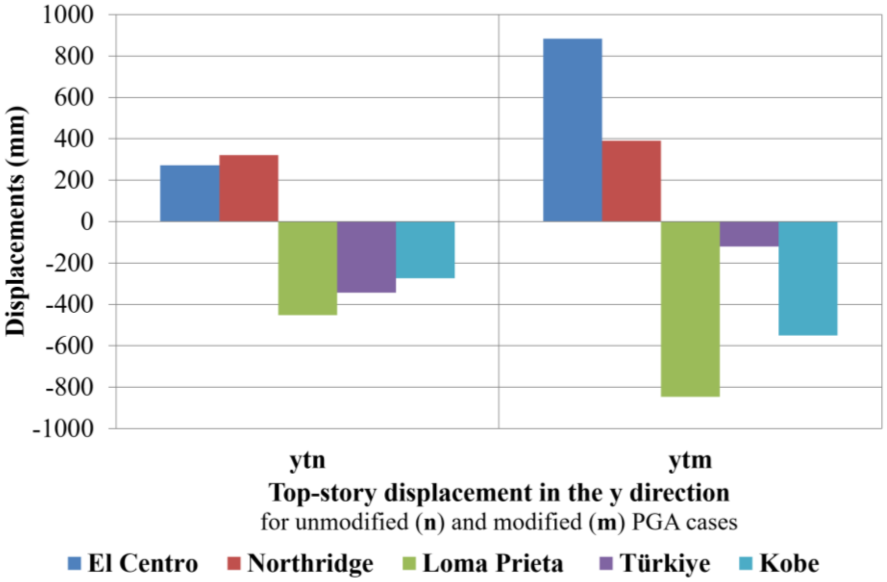
Fig. 6. Lateral displacements at foundation under different earthquake records

In contrast, the Kobe record, despite having a similar dominant period, exhibits different waveform characteristics and energy distribution, resulting in comparatively lower displacement response. Furthermore, the Türkiye (2023) earthquake, although characterized by high peak ground acceleration, is dominated by high-frequency content with a much shorter period, limiting resonance interaction with the structure and leading to smaller global displacements. When the records are scaled to a common peak ground acceleration (PGA = 0.7128 g), differences in amplitude are removed, and the response becomes more sensitive to frequency content, pulse characteristics, and waveform shape. Consequently, the relative ranking of displacement responses among the earthquake records changes, highlighting that seismic demand is governed not only by intensity measures such as PGA but also by the compatibility between ground-motion characteristics and the dynamic properties of the structure.

It is further observed that, in some cases, scaling the earthquake records to a common peak ground acceleration (PGA) does not significantly alter the overall structural response. This can be explained by the fact that PGA alone is not sufficient to fully characterize the damaging potential of ground motions, particularly for flexible high-rise structures. The response is strongly governed by the frequency content, spectral energy distribution, duration of strong shaking, and the presence of pulse-like features. Since these characteristics remain unchanged during linear amplitude scaling, the dynamic interaction between the ground motion and the structure is preserved. In particular, the degree of compatibility between the dominant ground-motion period or pulse period and the fundamental structural period continues to control the response. As a result, ground motions with similar spectral characteristics relative to the structural period may produce comparable response levels even after scaling, whereas records with different frequency content may still lead to significantly different structural demands despite having identical PGA values.



(a) Lateral displacements at the top of the building in the x direction



(b) Lateral displacements at the top of the building in the y direction

Fig. 7. Lateral displacements at the top of the building under different earthquake records

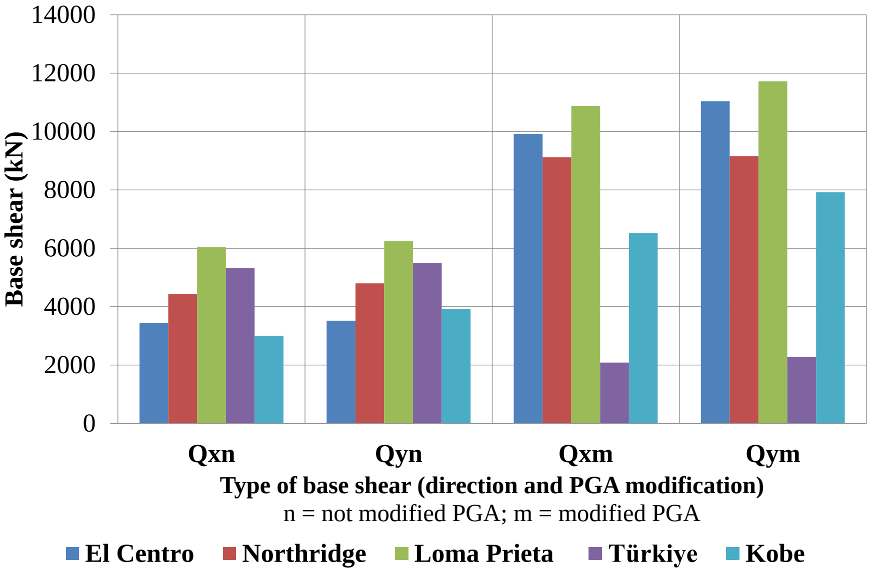
Figure 8 illustrates the straining actions of the building subjected to different earthquake records. Figure 8(a) presents the base shear responses in the x and y directions for both unmodified (natural) and modified earthquake records. For the modified earthquake cases, the base shear values in the two directions are nearly identical. This behavior can be attributed to the symmetry of the building's structural plan and the square cross-sections of its columns. For the unmodified earthquake records (Qxn and Qyn), the maximum base shear occurs under the Loma Prieta earthquake, while the minimum base shear is observed for the El Centro earthquake. Similarly, for the modified earthquake records (Qxm, Qym), the maximum base shear is again associated with the Loma Prieta earthquake, whereas the minimum base shear occurs for the Türkiye earthquake.

Figure 8(b) presents the base bending moments in the x and y directions for the building subjected to five different earthquake records. For the unmodified (natural) earthquake records (Mxn, Myn), the maximum base moments are observed for the Northridge earthquake, while the minimum base moments occur for the Kobe earthquake. In the case of the modified earthquake records (Mxm, Mym), the maximum base moments occur under the Loma Prieta earthquake, whereas the minimum values are obtained for the Türkiye earthquake.

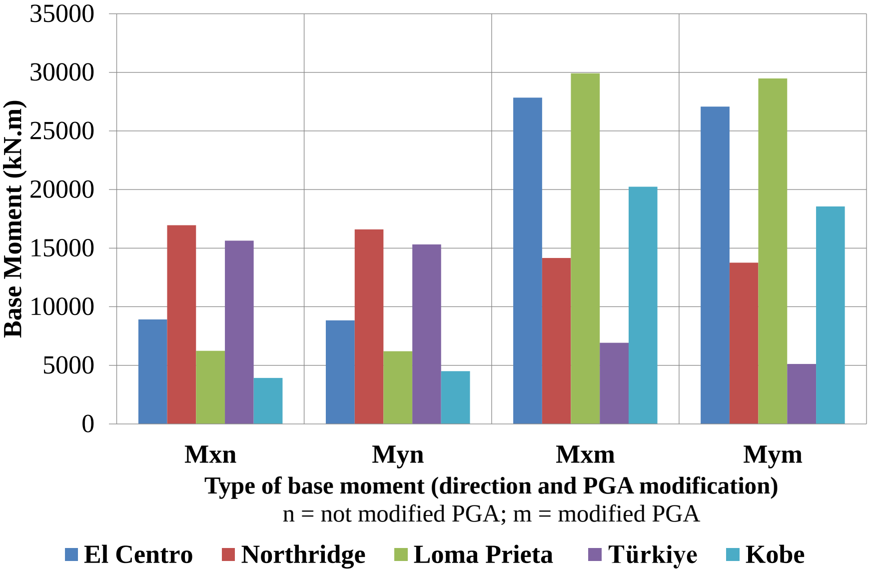
Figure 8(c) illustrates the ratio of base axial forces ($\mathrm{N = N_m/N_n}$) between modified and unmodified earthquake records for the five considered earthquakes. The highest axial force ratio corresponds to the El Centro earthquake, whereas the lowest ratio is associated with the Türkiye earthquake. These results also demonstrate that normalization based solely on peak ground acceleration does not lead to uniform structural response, and that frequency content, waveform characteristics, and pulse-like effects play a dominant role in governing the nonlinear behavior of flexible high-rise structures. The earthquake characteristics are consistent with the structural response results presented in Figures 6, 7 and 8, where earthquake records with long-period or pulse-like ground-motion components produce greater lateral displacements and increased base shear and bending moments, while records dominated by higher-frequency content result in comparatively smaller global responses in the flexible high-rise structure.

The larger lateral displacements observed under the Loma Prieta earthquake can be attributed to its long-period frequency content, which is relatively close to the fundamental period of the analyzed high-rise building. Spectral analysis indicates that the Loma Prieta record has a dominant period of approximately 1.60 s, which approaches the fundamental structural period ($\mathrm{T_1} \approx 2.073$ s). The Fourier amplitude spectrum of the Loma Prieta (1989) earthquake shows dominant frequency peaks corresponding to periods between approximately 1.2 s and 2.0 s, indicating the presence of low-frequency (long-period) ground-motion components, which can significantly influence flexible high-rise structures. When the dominant period of the ground motion approaches the structural period, the structure experiences resonance-like dynamic amplification, resulting in increased lateral displacement and drift demands. In addition, the Loma Prieta ground motion contains pulse-like characteristics associated with near-fault effects, which concentrate a large portion of seismic energy into a small number of cycles. This concentration of energy further amplifies the structural response, particularly in flexible structures such as high-rise buildings, leading to the larger displacement values observed in the numerical results.

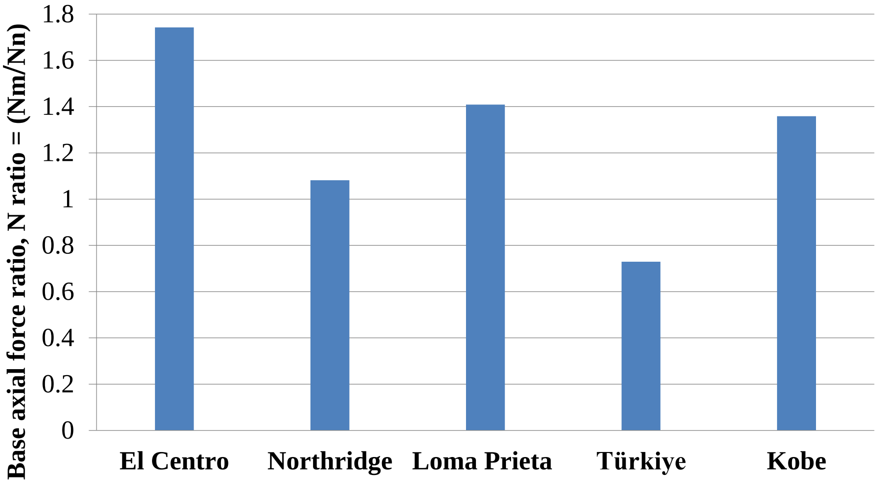
The El Centro (1940) record, characterized by a relatively short dominant period (≈0.42 s) and broad frequency content, represents a typical far-field motion without a clear pulse-like feature. The relatively large structural response observed under the El Centro (1940) earthquake can be attributed to the long duration and broad frequency content of the ground motion. Although the dominant period of the El Centro record (≈ 0.42 s) is shorter than the fundamental period of the analyzed 15-story structure ($T_1 \approx 2.073$ s), the ground motion contains a wide range of frequency components and multiple strong acceleration peaks distributed over time. The presence of spectral energy extending up to approximately 1.5–2.0 s indicates that the record still includes components capable of influencing more flexible structural systems. Moreover, the repeated loading cycles allow seismic energy to accumulate in the structure, which may increase lateral displacements and internal forces. Consequently, even ground motions dominated by relatively high-frequency components can produce significant structural response when the duration of strong shaking is sufficiently long.



(a) Base shear forces



(b) Base bending moments



**n** = not modified PGA case;
**m** = modified PGA case

(c) Ratio of base axial forces.

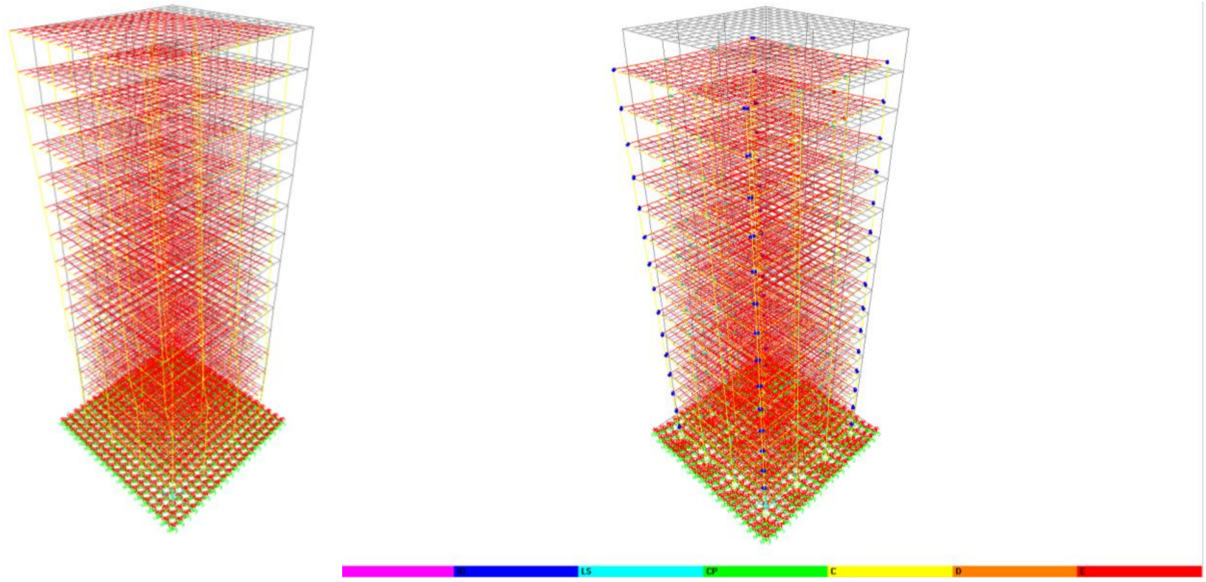
Fig. 8. Straining actions under different earthquake records

The relatively smaller lateral displacements observed for the Türkiye (Kahramanmaraş, 2023) earthquake after scaling can be attributed to its high-frequency seismic content, which is significantly different from the fundamental period of the analyzed high-rise structure. Spectral analysis indicates that the Türkiye record has a dominant period of approximately 0.15 s, corresponding to high-frequency ground motion. Since this period is much smaller than the fundamental structural period ($T_1 \approx 2.073$ s), the dynamic interaction between the ground motion and the structure is limited, reducing the potential for resonance-like amplification. As a result, despite the relatively large peak ground acceleration of the Türkiye earthquake, the structure experiences smaller global displacement response compared with earthquakes containing longer-period components. This observation highlights that ground-motion frequency content can be more influential than peak ground acceleration alone in determining the seismic response of flexible high-rise buildings.

Overall, the numerical results demonstrate that the seismic response of the analyzed high-rise building is strongly influenced by the frequency characteristics of the earthquake records. Ground motions with longer dominant periods, such as the Loma Prieta (1989) and Kobe (1995) earthquakes, produce larger lateral displacement and drift demands, since their dominant periods are relatively close to the fundamental structural period ($T_1 \approx 2.073$ s ). In contrast, earthquakes characterized by higher-frequency content, such as Türkiye (2023) records, generate comparatively smaller global displacement responses, because their dominant periods are much shorter than the structural period and therefore do not produce resonance-like amplification. The Northridge (1994) record exhibits moderate frequency characteristics, resulting in an intermediate structural response. These observations highlight that ground-motion frequency content and waveform characteristics can significantly influence structural behavior, even when earthquake records are scaled to the same peak ground acceleration level. Consequently, relying solely on PGA as an intensity measure may not adequately represent the seismic demand on flexible high-rise buildings, emphasizing the importance of considering frequency content and pulse-like ground-motion characteristics in nonlinear seismic performance assessments.

Pulse-like ground motions are characterized by the presence of a distinct large-amplitude velocity pulse occurring within a short duration, typically associated with forward-directivity effects in near-fault regions. These pulses concentrate a significant portion of the seismic energy into a limited number of loading cycles, which can lead to increased structural response, particularly in flexible systems. The identification of pulse-like characteristics in the selected earthquake records was performed based on inspection of acceleration time histories and is consistent with established approaches in the literature. In particular, Mavroeidis and Papageorgiou [4] proposed analytical representations of near-fault pulse-type motions, while Baker [5] introduced quantitative classification methods based on wavelet analysis for identifying velocity pulses. Based on these criteria, the Northridge (1994), Loma Prieta (1989), Kobe (1995), and Türkiye (2023) earthquake records were identified as exhibiting pulse-like characteristics, whereas the El Centro (1940) record represents a typical non-pulse far-field ground motion. The observed response trends further confirm that the seismic demand is critically controlled by the ratio between the pulse period ($T_p$) and the fundamental structural period ($T_1$), as maximum amplification occurs when $T_p \approx T_1$, resulting in resonance-like dynamic effects that significantly increase lateral displacements and drift demands, particularly in flexible high-rise structures. In the present study, this mechanism is evident in the response to the Loma Prieta and Kobe earthquake records, where pulse periods approaching the fundamental structural period ($T_1 \approx 2.073$ s) result in increased displacement demands; however, the differences observed between these cases indicate that the $T_p/T_1$ ratio alone does not fully govern the response, as factors such as spectral energy distribution, pulse amplitude, and duration of strong motion also play a critical role.

Figure 9 illustrates a representative structural deformed configuration and plastic hinge distribution under the Loma Prieta earthquake, which produced the maximum lateral displacement among the considered records.



(a) Deformed shape (b) Plastic hinge distribution overlaid on the deformed configuration

Fig. 9. Representative nonlinear structural response under Loma Prieta earthquake excitation: (a) Deformed configuration of the 15-story building at peak lateral displacement (scale factor = 20), illustrating the global lateral sway pattern; and (b) Corresponding plastic hinge distribution overlaid on the deformed configuration at peak response, where the color-coded hinges represent different performance levels according to SAP2000 conventions: purple indicates yielding (B), blue corresponds to Immediate Occupancy (IO), cyan represents Life Safety (LS), green denotes Collapse Prevention (CP), yellow indicates the onset of post-collapse-prevention degradation (C), orange indicates advanced strength degradation (D), red represents failure (E)

Figure 9(a) shows that the largest lateral deformation occurs in the upper stories, consistent with the flexible response of high-rise moment-resisting frame systems under long-period seismic excitation. Figure 9(b) presents the plastic hinge distribution at peak response. The nonlinear response is mainly concentrated in beam and column elements in the lower and intermediate stories, where seismic demands and internal force concentrations are typically highest. This pattern reflects the progressive development of inelastic action in RC frame structures subjected to severe ground motion. The observed hinge formation confirms that the selected earthquake record induces significant nonlinear structural behavior, supporting the use of nonlinear time-history analysis in this study.

The adopted medium soil condition influences the obtained response through foundation flexibility and radiation damping represented by the spring–dashpot SSI model. This flexibility increases the effective deformability of the soil–foundation–structure system and may contribute to larger lateral displacement demands, particularly under long-period and pulse-like ground motions. At the same time, the damping component of the soil model contributes to energy dissipation and can modify the transmitted base shear and bending moments. Therefore, the response trends shown in Figs. 6–8 are not governed only by the earthquake records, but also by the assumed medium soil properties and their influence on the dynamic characteristics of the coupled system.

## 7. Conclusions

A three-dimensional 15-story building was analyzed under five different earthquake records to investigate the influence of variations in earthquake characteristics on the seismic response of the high-rise building (HRB), considering soil-structure interaction (SSI) effects. Lateral displacements in the x and y directions, base shear forces, base bending moments, and base axial force ratios obtained from modified and unmodified earthquake records were used to evaluate the structural performance of the building. Based on the observed displacement and force responses, the following conclusions are drawn:

- Soil-structure interaction (SSI) has a significant influence on the seismic response of high-rise buildings (HRBs) and should be explicitly considered in time-history analyses.
- Finite element modeling (FEM) is essential for reliably capturing the dynamic behavior of HRBs subjected to earthquake loading.
- Reliable seismic performance assessment of HRBs requires evaluation using multiple earthquake records prior to final structural design.
- Long-period earthquake records can result in higher lateral displacements in HRBs compared with short-period earthquake records.
- Nevertheless, high peak ground acceleration (PGA) associated with certain earthquake frequency contents does not necessarily lead to the most severe straining actions in HRBs.
- Variations in the frequency content and waveform characteristics of the earthquake records result in noticeable differences in the base shear response, with variations of up to approximately 20% among the considered earthquakes.
- Similarly, the base bending moments exhibit noticeable variations among the considered earthquake records, with differences reaching up to approximately 25% due to variations in the frequency content and waveform characteristics of the ground motions. However, in some cases, scaling the ground motions to a common PGA does not significantly alter the overall structural response.
- Overall, the results indicate that ground motions with dominant or pulse periods approaching the fundamental period of the structure produce the largest lateral displacement and drift demands, highlighting the critical role of frequency content and pulse characteristics in the seismic response of flexible high-rise buildings.

Future studies may extend the present work by investigating a broader range of building configurations, varying soil conditions, and a larger suite of near-fault earthquake records for statistical evaluation. Further research could also incorporate a detailed assessment of plastic hinge formation and hysteretic response. The adopted numerical modeling methodology is based on validated finite-element procedures and soil–structure interaction (SSI) formulations widely accepted in previous literature for the nonlinear seismic assessment of reinforced concrete high-rise buildings.

## References

[1] Aki K. Local site effects. In: Von Thun JL, editor. Earthquake Engineering and Soil Dynamics II. Geotechnical Special Publication No. 20. ASCE; 1988:103-155.

[2] Somerville PG. Emerging art: earthquake ground motions. In: Geotechnical Earthquake Engineering and Soil Dynamics III. Proceedings of the ASCE Geotechnical Special Publication No. 75. Seattle (USA): ASCE; 1998:1-38.

[3] Romo MP, Mendoza MJ, Garcia SR. Geotechnical factors in seismic design of foundations: state-of-the-art report. Bulletin of the New Zealand Society for Earthquake Engineering. 2000;33(3):347-370. https://doi.org/10.5459/bnzsee.33.3.347-370

[4] Mavroeidis GP, Papageorgiou AS. A mathematical representation of near-fault ground motions. Bulletin of the Seismological Society of America. 2003;93(3):1099-1131. https://doi.org/10.1785/0120020100

[5] Baker JW. Quantitative classification of near-fault ground motions using wavelet analysis. Bulletin of the Seismological Society of America. 2007;97(5):1486-1501. https://doi.org/10.1785/0120060255

[6] Tothong P, Cornell CA. Structural performance assessment under near-source pulse-like ground motions using advanced ground motion intensity measures. Earthquake Engineering and Structural Dynamics. 2008;37(7):1013-1037. https://doi.org/10.1002/eqe.775

[7] Chopra AK. Dynamics of structures: theory and applications to earthquake engineering. 5th ed. Boston: Pearson Education; 2017.

[8] Wang H, Zhang R. Dynamic structure-soil-structure interaction of piled high-rise buildings under earthquake excitations I: influence on dynamic response. Latin American Journal of Solids and Structures. 2021;18(3):e357. https://doi.org/10.1590/1679-78256223

[9] Jia H, Song Y, Chen X, Liu S, Zhang B. Seismic performance evaluation of a high-rise building with structural irregularities. Buildings. 2022;12(9):1484. https://doi.org/10.3390/buildings12091484

[10] Kato B, Wang G. Seismic site–city interaction analysis of super-tall buildings surrounding an underground station: a case study in Hong Kong. Bulletin of Earthquake Engineering. 2022;20:1431-1454. https://doi.org/10.1007/s10518-021-01295-7

[11] Alothman A, Mangalathu S, Al-Mosawe A, Alam M, Allawi A. The influence of earthquake characteristics on the seismic performance of reinforced concrete buildings in Australia with varying heights. Journal of Building Engineering. 2023;67:105957. https://doi.org/10.1016/j.jobe.2023.105957

[12] Wei H, Zhang B, Tang Y, Mao K. Seismic performance investigation of irregular and complex connected structures based on the influence of ground fissure activity. Journal of Building Engineering. 2024;91:109661. https://doi.org/10.1016/j.jobe.2024.109661

[13] Salem GG. Natural frequency of buildings and resonance phenomenon: impacts on structural design. ERU Research Journal. 2025;4(2):2505-2525. https://doi.org/10.21608/erurj.2025.290623.1144

[14] Kontoni DPN, Farghaly AA. The effect of base isolation and tuned mass dampers on the seismic response of RC high-rise buildings considering soil-structure interaction. Earthquakes and Structures. 2019;17(4):425-434. https://doi.org/10.12989/eas.2019.17.4.425

[15] Farghaly AA, Kontoni DPN. Mitigation of seismic pounding between RC twin high-rise buildings with piled raft foundation considering SSI. Earthquakes and Structures. 2022;22(6):625-635. https://doi.org/10.12989/EAS.2022.22.6.625

[16] Kontoni DPN, Farghaly AA. Enhancing the earthquake resistance of RC and steel high-rise buildings by bracings, shear walls and TMDs considering SSI. Asian Journal of Civil Engineering. 2023;24:2595-2608. https://doi.org/10.1007/s42107-023-00666-6

[17] Farghaly AA, Kontoni DPN. Mitigation of seismic pounding between two L-shape in plan high-rise buildings considering SSI effect. Coupled Systems Mechanics. 2023;12(3):277-295. https://doi.org/10.12989/csm.2023.12.3.277

[18] Kontoni DPN, Farghaly AA. Investigation of the effect of energy piles on the seismic response of RC high-rise building with piled raft foundation. Coupled Systems Mechanics. 2024;13(5):433-457. https://doi.org/10.12989/csm.2024.13.5.433

[19] Kontoni DPN, Farghaly AA, El-Shater AH, Mohamed MA. Numerical FEM and experimental investigation of soil-pile-structure interaction on the seismic response of RC high-rise buildings with rafted pile foundations and various pile configurations. Journal of Structural Integrity and Maintenance. 2025;10(4):2567083. https://doi.org/10.1080/24705314.2025.2567083

[20] SAP2000. Integrated software for structural analysis and design. Version 25. Walnut Creek (CA): Computers and Structures Inc.; 2023. Available from: https://www.csiamerica.com/products/sap2000

[21] Newmark NM, Rosenblueth E. Fundamentals of earthquake engineering. Englewood Cliffs (NJ): Prentice-Hall; 1971.