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Seismic Response of Vertical Hybrid Concrete/Steel Frames Considering Soil–Structure Interaction

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Abstract: The aim of this study is to investigate the seismic behavior of concrete/steel mixed structures. In engineering praxis, many buildings consist of two parts: one made of reinforced concrete and the other made of steel. There are several difficulties in the code-based seismic design of these structures due to the different dynamic responses of each discrete part. Seismic design codes, such as the IBC and Eurocode 8, do not provide instructions for structures consisting of two parts. In addition, they use a single-loading scenario, but there are many locations that are affected by more than one earthquake in a short period. Another drawback is that recent provisions do not consider soil–structure interaction effects. The specific issue addressed here is the seismic response of mixed structures, which is evaluated through inelastic time–history analysis. More specifically, the response indices involve height-wise distributions for peak interstory drift ratios, maximum floor horizontal displacements, maximum floor accelerations, and plastic hinge formations in the frame elements when they are subjected to seismic sequences of earthquakes, as well as in far fault ground motions for different soil types. The results reveal that sequential ground motions lead to increased displacement demands, and they affect the permanent displacements. This phenomenon appears in both cases of stiff and flexible soil, as well as for both regular and irregular frames. It is found that soil–structure interaction generally leads to lower values of IDR, and maximum horizontal displacement and acceleration in comparison with the case of rigid soil assumptions.

Keywords: mixed structures; soil–structure interaction; seismic sequences; regular and irregular frames

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1. Introduction

The purpose of the present work is to investigate the seismic response of mixed concrete/steel structures consisting of two parts: a lower made of reinforced concrete and an upper made of steel. The response of two parts when the structure is subjected to seismic excitation is different. This has to do with the material distribution over the height of the structure; for example, the primary structure is made of concrete and the superstructure is made of steel, and this leads to different damping properties of the two parts as well as different hysteretic behavior. There are many concrete/steel mixed structures in everyday engineering practice. The most common application is to add steel stories above existing concrete structures (Figure 1). This leads to a reduction of additional dead weight and to the speed of construction.

Modern seismic codes provide recommendations for buildings with the same material throughout the whole structure, while they do not include provisions for such irregular (mixed) structures when subjected to earthquakes. They only give instructions for secondary structures, e.g., antennas and chimneys, where their material can be different from that of the main structure. Various researchers have carried out studies in order to provide an understanding of their seismic behavior, and there are two categories of analysis: the decoupled and the coupled. In the decoupled approach, the parts of the structure are analyzed separately, while in the coupled one, the designer has to analyze the whole model.

Chen and Soong [1] performed a modal analysis in hybrid structures, and Papageorgiou and Gantes [2] found that the decoupling procedure is suitable for the estimation of the seismic response of the structure. Medina et al. [3], Rao et al. [4], and Chaudhuri and Gupta [5] estimated the error of decoupling. The nonlinear behavior of "vertically" mixed structures has been studied by Askouni and Papagiannopoulos [6]. The term "vertically" denotes the addition of steel structures above concrete. Another type is the "horizontally" mixed structures, where there are different materials in the same story.

Figure 1. Mixed concrete/steel structure.

Seismic code provisions set different damping levels for each material, and this leads to the difficulty of designing a structure with different parts since traditional assumptions of structural dynamics, such as the Rayleigh damping approach, cannot be applied in this case. These codes do not provide specifications for the design of mixed structures under seismic excitations. Another drawback of the codes is that the influence of repeated earthquake phenomena is ignored. In several locations worldwide, the sequence of seismic events, which consists of a main event (mainshock) and several aftershocks with similar intensity, has increased the interest of the researchers. Sequential events have occurred in California (Mammoth Lakes, 1980; Coalinga, 1983; Whittier Narrows, 1987; Northridge 1994), Italy (Friuli, 1976; Irpinia, 1980; Umbria-Marche, 1997; L'Aquila,2009), Japan (Kobe, 1995; Niigata, 2004; Tohoku, 2011), New Zealand (Darfield, 2010; Christchurch, 2011), and Turkey (Van, 2011). Several studies have examined the effect of aftershocks on reinforced concrete frames [7–11], steel frames [12,13], and wood frames [14]. Hatzigeorgiou et al. [7,15] and Askouni [16] have concluded that displacement demands are increased when structures are subjected to seismic sequences. In Mahin's study [17], it was demonstrated that the demand for ductility in single degrees of freedom systems increased due to the aftershocks. Similar results are found in the study of Aschheim and Black [18]. Elnashai et al. [19] found that the sequential events provoke higher ductility demands than one single event. However, the effects of sequential ground motions on the mixed concrete/steel structures have not been investigated yet.

Another limitation of the recent seismic codes is that they usually neglect soil–structure interaction phenomena because they assume that their omission leads to conservative results [20,21]. On the contrary, it has been observed [22,23] that structures founded on rigid soil have different seismic behavior than that of structures founded on compliant soil. This has to do with the alteration of the dynamic characteristics of the system, where the flexibility of soils can lead to increased deformation [21,24]. Furthermore, the nonlinear behavior of the superstructure and its damage is strongly affected by the response of the foundation and soil. This is remarkable in the case of historical earthquakes, such as Loma Prieta [25] and Kobe [26].

Taking into account the aforementioned gaps in the pertinent literature, the first objective of this study is to investigate the seismic response of mixed concrete/steel structures under the action of seismic sequences. The second objective is to examine their seismic behavior considering the soil–structure interaction (SSI) effects. For these reasons, three- and four-story mixed frames, regular and irregular along their height, are examined under various real seismic sequences and numerous single far-fault seismic ground motions. In order to evaluate their seismic response, time history analysis has been conducted with the aim of SAP 2000 seismic analysis software [27]. The most important structural parameters, such as height-wise distributions for peak interstory drift ratios (IDR), maximum floor horizontal displacements, maximum floor accelerations, and plastic hinge formation, are computed and discussed.

2. Description of Structures

Three- and four-story, regular, and vertically irregular mixed buildings are considered here. They consist of three bays with equal lengths of 5 m (total length: 15 m). The story height is equal to 3 m. These frames have been designed according to Eurocode 8 [28] provisions, assuming ground acceleration equal to 0.36 g and soil class B.

The structures have been designed for the loading combinations of EC8 [28]:

$$\begin{aligned} &(a)\ 1.35G + 1.50Q, \\ &(b)\ 1.00G + \psi Q + 1.00E, \\ &(c)\ 1.00G + \psi Q - 1.00E, \end{aligned} \tag{1}$$

where G (=22 kN/m), Q (=11 kN/m), and E correspond to dead, live, and earthquake loads, respectively, and ψ (=0.5) is the coefficient for live load

Assuming that the viscous damping ratio is 5% for concrete and 3% for steel, in this study, the viscous damping ratio of a mixed concrete/steel structure has been considered equal to 4%. The yield stress of steel was 235 MPa (steel S235), whereas the grade of concrete members was C20/25 (compressive cylinder strength of 20 MPa and cube strength of 25 MPa), and steel grade for longitudinal and transverse reinforcement was S500 (yield stress: 500 MPa). The concrete beam sections had dimensions: width × height = 30 cm × 40 cm, whereas concrete columns sections were square: 30 cm × 30 cm. The standard section of the steel beams was IPE330 and of steel columns HEB240 [29]. The characteristic frames, as well as the amount and arrangement of reinforcement of concrete members, are shown in Figures 2–5.

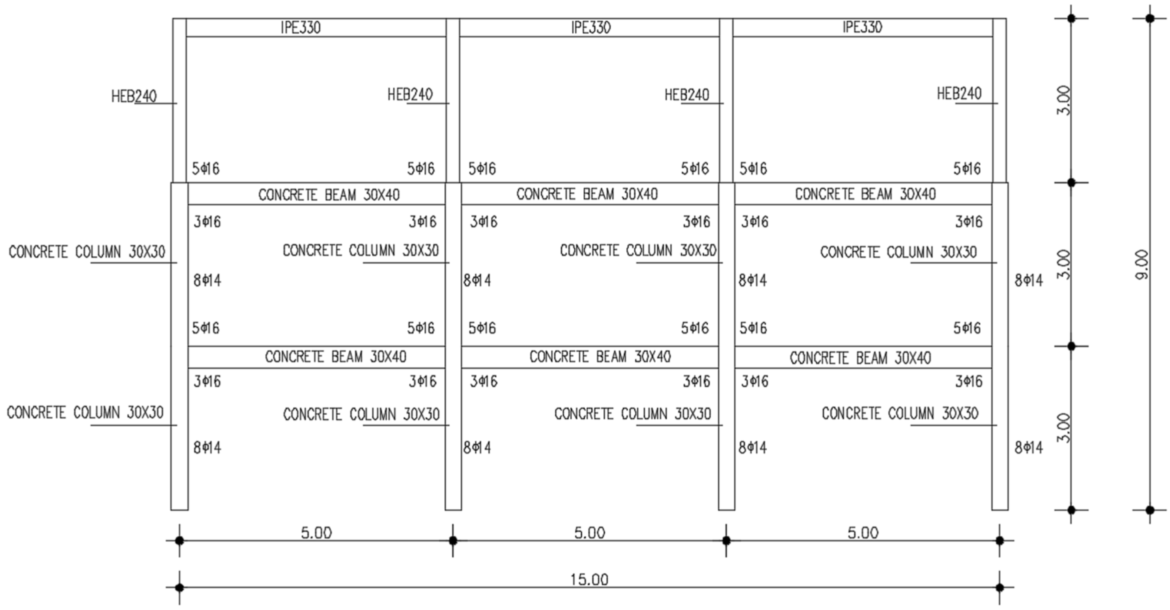

Figure 2. Mixed three-story regular frame.

The design of columns of frames must satisfy the following condition of §4.4.2.3 of EC8 [6] at all joints:

$$\sum M_{RC} \geq 1.3 \sum M_{RB} \tag{2}$$

where $\sum M_{Rc}$ and $\sum M_{Rb}$ are the sum of the of the moments of resistance of the columns and beams in the joint, respectively.

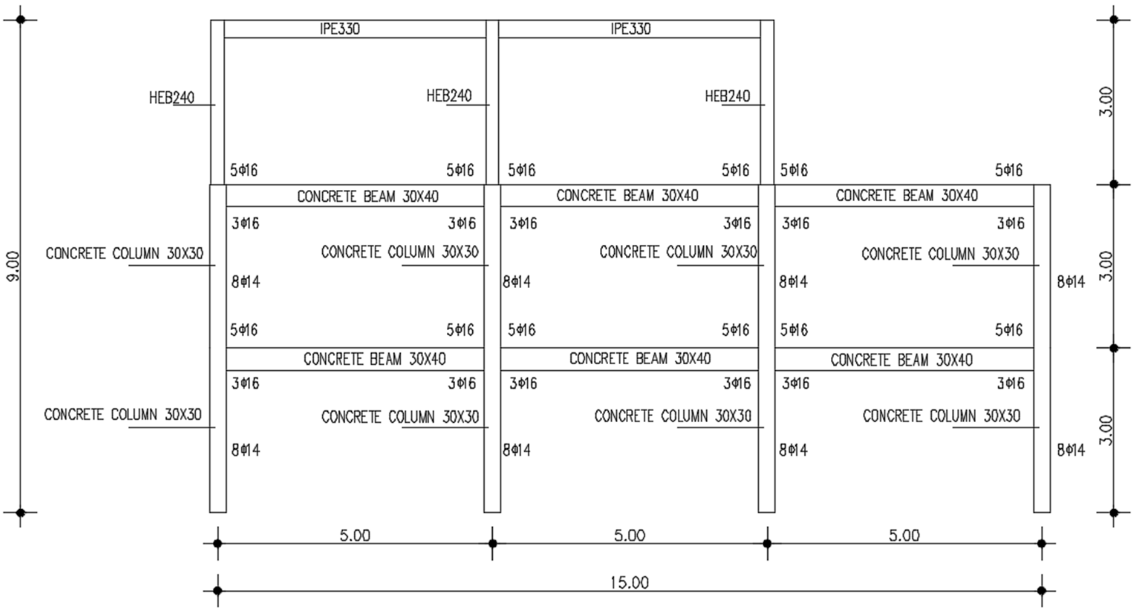

Figure 3. Irregular mixed three-story frame.

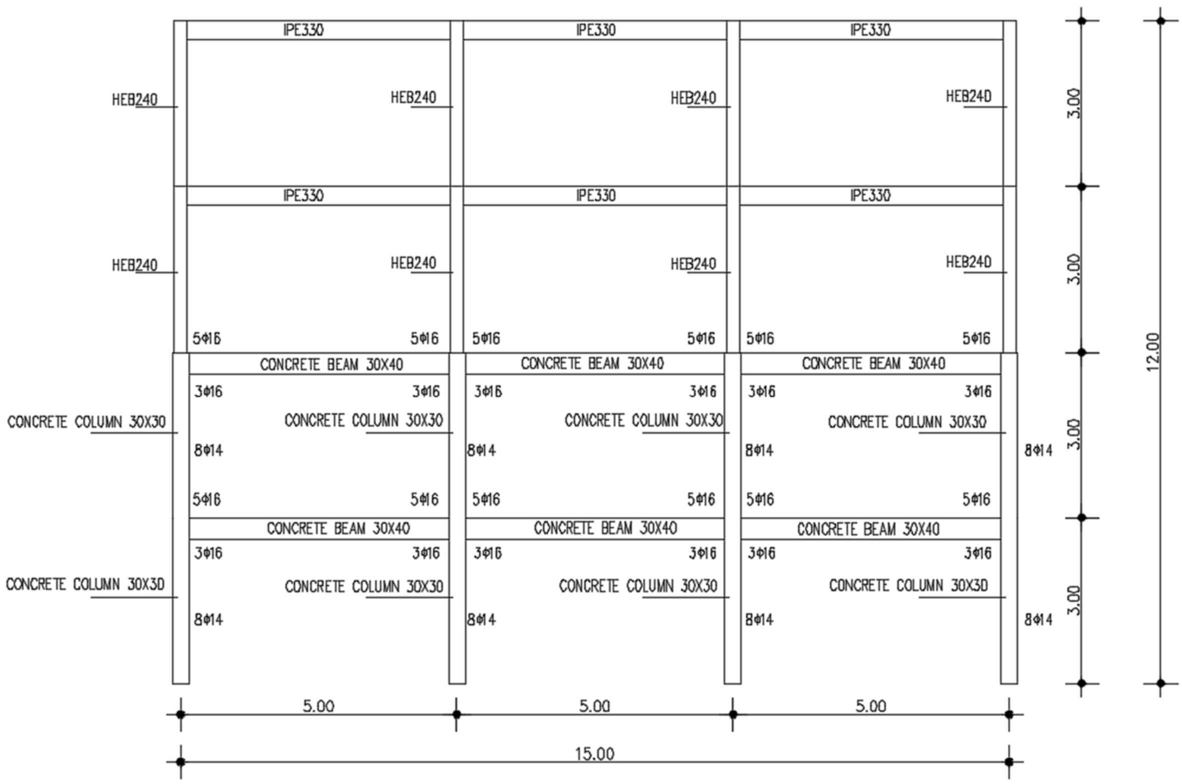

Figure 4. Mixed four-story regular frame.

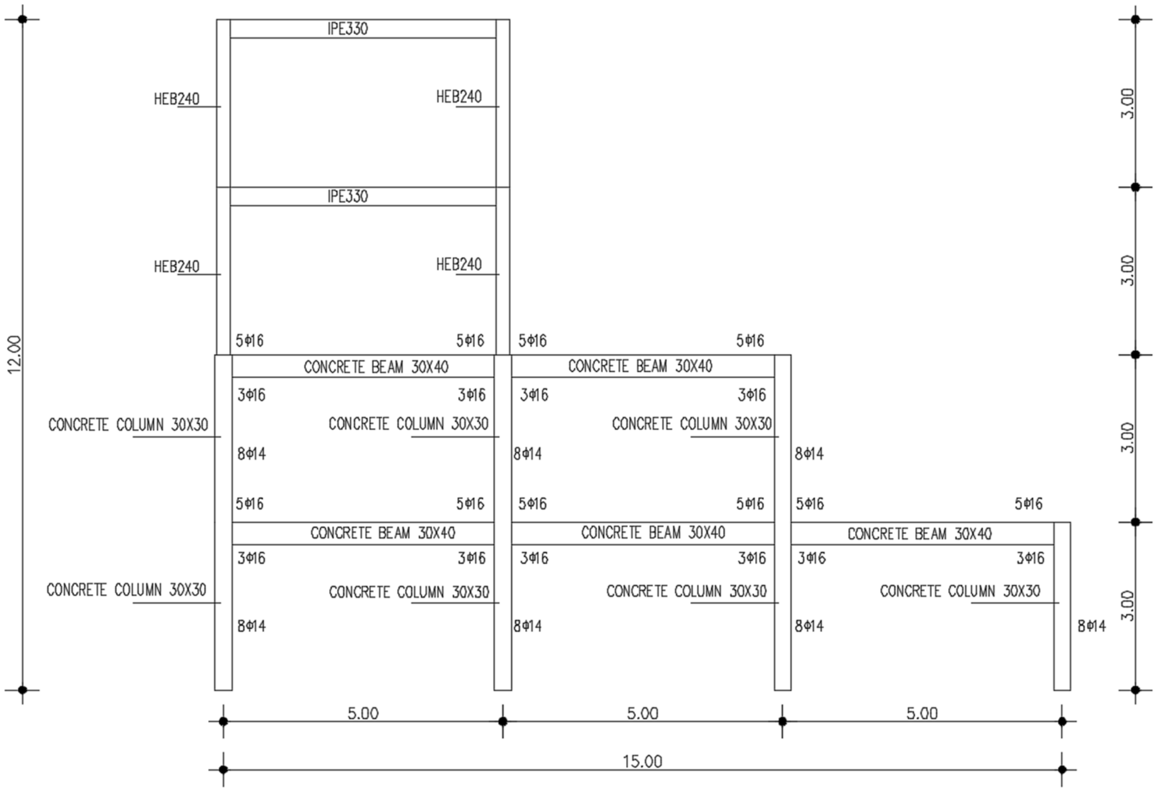

Figure 5. Irregular mixed four-story frame.

The behavior factor according to EC8 [28] for regular mixed structures was 3.9, and for irregular frames, the behavior factor must decrease by 20%, which leads to q = 0.8 × 3.9 = 3.12. A typical model (mixed three-story regular frame), which has been created in SAP2000 [27], is shown in Figure 6.

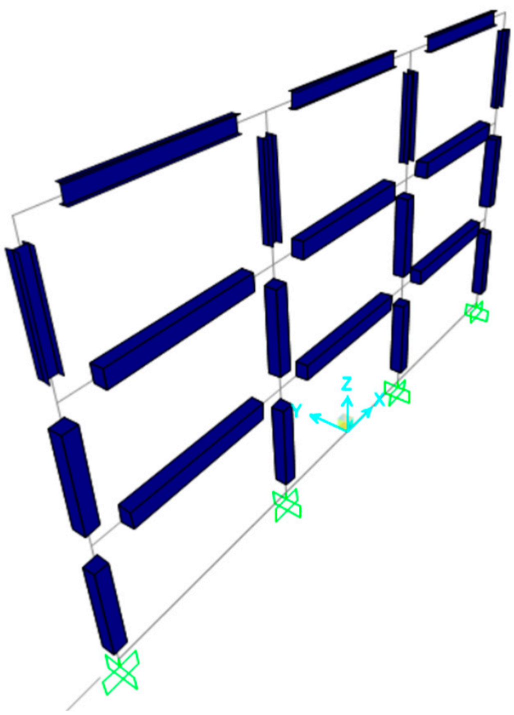

Figure 6. The 2D Model in SAP 2000 [27] for a mixed frame founded on rigid soil.

The nonlinear frame elements representing beam and column elements in the model incorporate concentrated plasticity. This is achieved by introducing plastic hinges at both ends of the beams and beams–columns. The determination of the plastic hinge length is of utmost importance as it establishes the relationship between rotation values and curvatures. Numerous plastic hinge lengths have been suggested in various literature sources. However, for the purpose of this study, we adopt the simplest approach proposed by Park and Paulay [30]. According to this approach, the plastic hinge length for each member was set as half of its section's height. The seismic behavior of the structures was evaluated through nonlinear time–history analysis (NTHA). The diaphragm action of the concrete slab has been taken into account due to the existence of rigid floors, which leads to the absence of axial forces of the beams. Geometrical nonlinearities have been considered. Beams and columns are modeled as nonlinear standard frame elements with concentrated plasticity near their ends. Plastic hinges in columns are created due to the interaction of axial force—bending moments and plastic hinges in beams are formed due to uniaxial bending. In this study, we employed an effective stiffness for concrete members according to ASCE 41-17 [31]. More details about the limits of plastic hinge rotations can be found in ASCE 41-17 [31].

2.1. Seismic Motions

The first set of seismic ground motions appear in Table 1 and has to do with the seismic sequences of Mammoth Lakes, Chalfant Valley, Coalinga, Imperial Valley, and Whittier Narrows earthquakes. Every record has been downloaded from the NGA database [32] and recorded by accelerometers that had been installed at locations characterized as soil class B [28]. Every record from the NGA database is considered as a single ground motion where, in this study, between two consecutive seismic events, a time gap of 100 s with zero acceleration is applied to cease the vibration of the previous seismic event before the next consecutive one. Single earthquakes, for every seismic sequence examined here, have been recorded by the same accelerometer during a period of three days.

Table 1. Seismic sequences.

No	Seismic Sequence	Station	Comp.	Date (Time)	Magnitude (ML)	Recorded PGA (g)
1	Mammoth Lakes	54099 Convict Creek	N-S	25 May 1980 (16:34)	6.1	0.442
				25 May 1980 (16:49)	6.0	0.178
				25 May 1980 (19:44)	6.1	0.208
				25 May 1980 (20:35)	5.7	0.432
				27 May 1980 (14:51)	6.2	0.316
2	Chalfant Valley	54428 Zack Brothers Ranch	E-W	20 July 1986 (14:29)	5.9	0.285
				21 July 1986 (14:42)	6.3	0.447
3	Coalinga	46T04 CHP	N-S	22 July 1983 (02:39)	6.0	0.605
				25 July 1983 (22:31)	5.3	0.733

Table 1. *Cont.*

No	Seismic Sequence	Station	Comp.	Date (Time)	Magnitude (ML)	Recorded PGA (g)
4	Imperial Valley	5055 Holtville P.O.	HPV315	15 October 1979 (23:16)	6.6	0.221
				15 October 1979 (23:19)	5.2	0.211
5	Whittier Narrows	24401 San Marino	N-S	1 October 1987 (14:42)	5.9	0.204
				4 October 1987 (10:59)	5.3	0.212

Figure 7 depicts the response spectra for these records. Furthermore, in order to thoroughly examine the behavior of mixed structures, a second set of single-ground motions is also considered. Thus, Table 2 displays the second set of seismic motions, which depicts details about the station, the component, date, magnitude, and recorded PGA. In order to comply with the design process, all ground motions of Tables have been recorded by accelerometers that had been installed on Soil B. Additionally, Figure 8 depicts the response spectra for these records, their mean spectrum, and the EC8 [28] design spectrum for Soil B. It is obvious that the mean spectrum of the selected single records matches well the design spectrum of EC8 [28]. The reader can also consult the pertinent studies of Demir et al. [33,34] for further information about the appropriate selection of seismic records.

Table 2. Recorded far-fault earthquake motions.

No.	Date	Record Name	Comp.	Station Name	PGA (g)
1.	4 October 1987	Whittier Narrows	NS	24399 Mt Wilson-CIT Station	0.158
2.	4 October 1987	Whittier Narrows	EW	24399 Mt Wilson-CIT Station	0.142
3.	20 September 1999	Chi-Chi, Taiwan	056-N	HWA056	0.107
4.	20 September 1999	Chi-Chi, Taiwan	056-N	HWA056	0.107
5.	1 October 1987	Whittier Narrows	NS	24399 Mt Wilson-CIT Station	0.186
6.	1 October 1987	Whittier Narrows	EW	24399 Mt Wilson-CIT Station	0.123
7.	9 February 1971	San Fernando	N069	127 Lake Hughes #9	0.157
8.	9 February 1971	San Fernando	N159	127 Lake Hughes #9	0.134
9.	17 January 1994	Northridge	NS	90019 San Gabriel-E. Gr. Ave.	0.256
10.	17 January 1994	Northridge	EW	90019 San Gabriel-E. Gr. Ave.	0.141
11.	20 September 1999	Chi-Chi, Taiwan	NS	TAP103	0.177
12.	20 September 1999	Chi-Chi, Taiwan	EW	TAP103	0.122
13.	17 January 1994	Northridge	N005	90017 LA-Wonderland Ave	0.172
14.	17 January 1994	Northridge	N175	90017 LA-Wonderland Ave	0.112
15.	7 June 1975	Northern Calif	N060	1249 Cape Mendocino, Petrolia	0.115
16.	7 June 1975	Northern Calif	N150	1249 Cape Mendocino, Petrolia	0.179
17.	8 July 1986	N. Palm Springs	NS	12206 Silent Valley	0.139
18.	18 October 1989	Loma Prieta	N205	58539 San Francisco	0.105
19.	18 October 1989	Loma Prieta	NS	47379 Gilroy Array #1	0.473
20.	18 October 1989	Loma Prieta	EW	47379 Gilroy Array #1	0.411

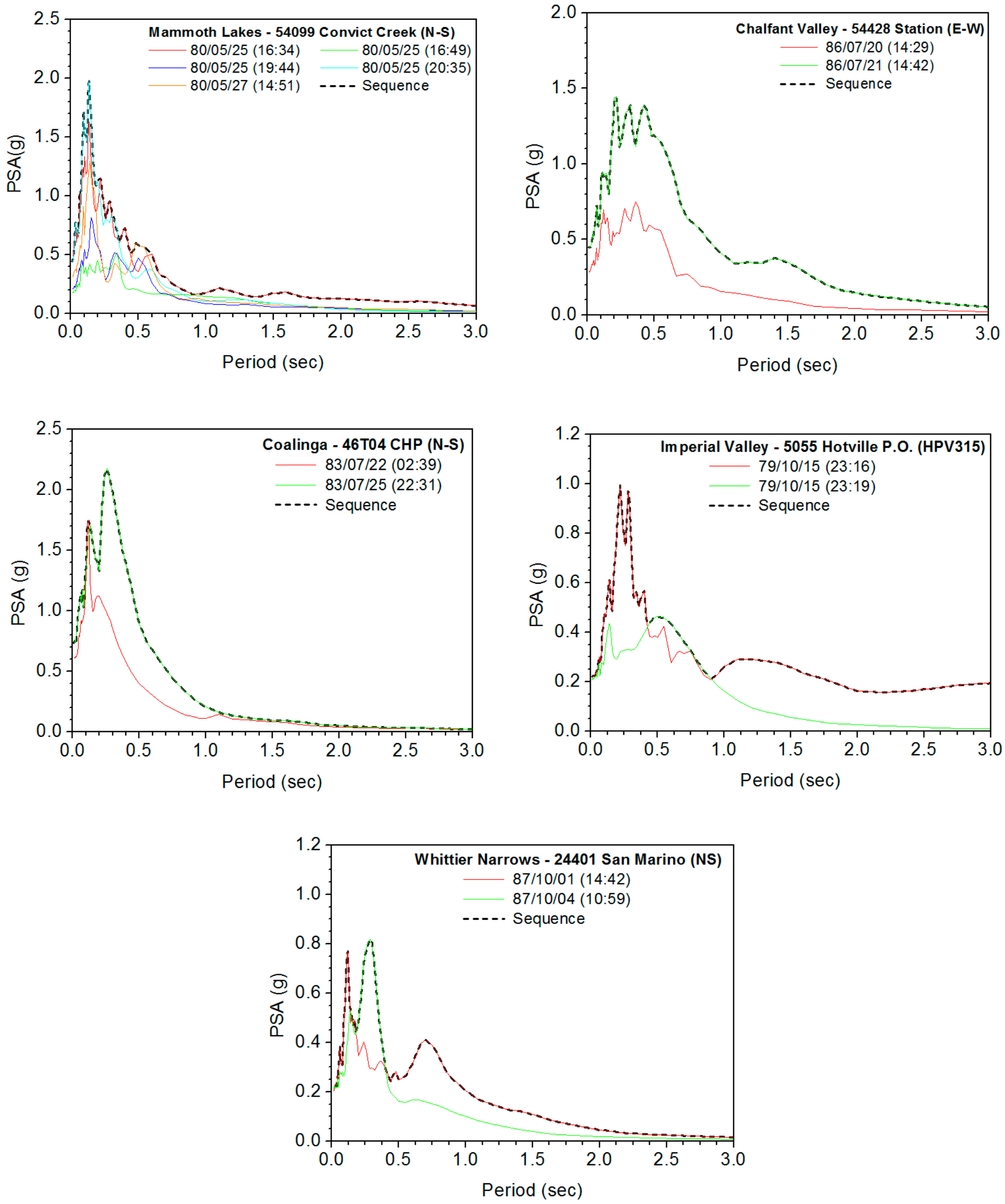

Figure 7. Response spectra of the examined seismic sequences.

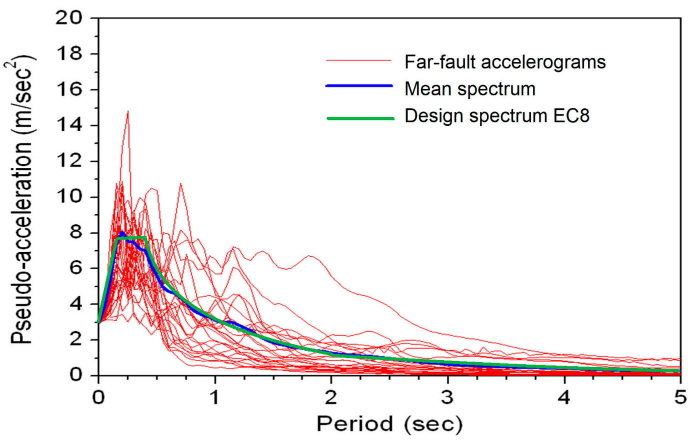

Figure 8. Response spectra of the examined single earthquakes and EC8 design spectrum.

2.2. Soil–Structure Interaction

The inclusion of a flexible foundation system can elongate the natural period of structures. This elongation is a result of soil–structure interaction (SSI), which has implications for seismic design in structures [35,36]. It is important to consider period elongation as it possibly will lead to increased demands on the structure [37]. In this subsection, the main variables that influence period-lengthening characteristics of mixed buildings due to SSI are examined. For the case of flexible soil, the foundation is modeled using a discrete system of frequency-independent springs and dashpots, which take into account horizontal and vertical translations of the foundation as well as its rocking [38]. Each concrete column has been supported by a 2 m × 2 m × 0.6 m footing, which has been designed according to Eurocode 8 [6]. It has been considered soil type B, with shear wave velocity equal to 360 m/s and soil density 2000 kg/m^3. Therefore, the design of the foundation is absolutely compatible with the aforementioned seismic ground motions. In order to take into consideration the nonlinearity of soil deformations for large ground accelerations, the effective shear modulus is assumed to be equal to 10% of its initial "elastic" value [39]. In order to model the system of springs, dashpots, and masses, the "link element" [27] is utilized. The coefficients of springs and damping coefficients of dashpots are presented in Table 3 and they are obtained from the following equations:

$$K_v = \frac{4.7G_0 a}{1-v} \tag{3}$$

$$K_H = \frac{9.2G_0 a}{2-v} \tag{4}$$

$$K_R = \frac{4G_0 a^3}{1-v} \tag{5}$$

$$C_v = \frac{0.8a}{V_s} K_v \tag{6}$$

$$C_H = \frac{0.163a}{V_s} K_H \tag{7}$$

$$C_R = \frac{0.6a}{V_s} K_R \tag{8}$$

where α is the half-width of the square foundation for every column, G_0, ν are the shear modulus and Poisson's ratio of the soil, respectively, V_S is the shear wave velocity of the soil.

Table 3. SSI coefficients.

Direction/Motion	Spring Coefficient (kN/m)	Dashpot Coefficient (kNs/m)
Vertical	174,000	1223
Horizontal	140,000	200.84
Rocking	148,000	780.63

Finally, the examined model, e.g., for the three-story mixed regular frame, appears in Figure 9.

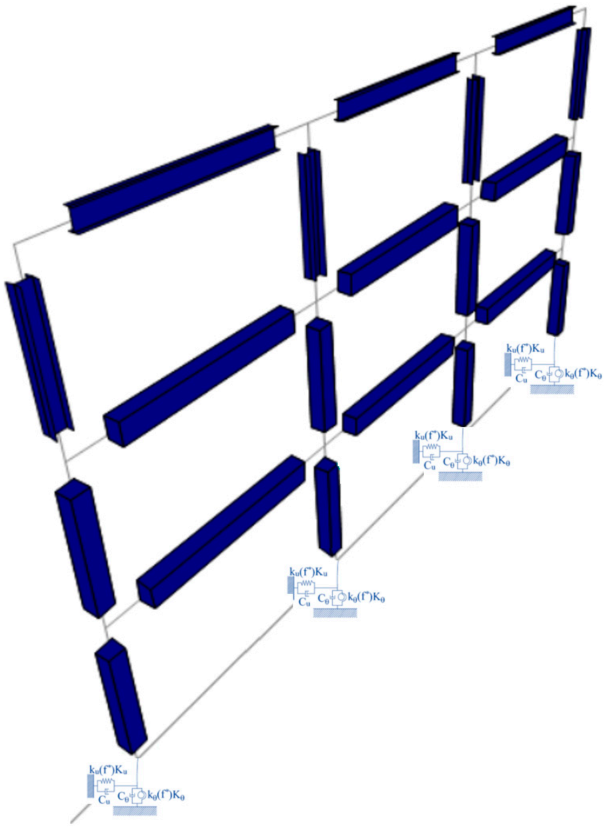

Figure 9. The 2D Model in SAP 2000 [27] for a mixed frame founded on deformable soil.

3. Behavior of Mixed Frames under Multiple Earthquakes: Selected Results

In this section, the nonlinear behavior of mixed concrete/steel structures is assessed by means of nonlinear time-history (NLTH) analyses employing five real (as recorded) seismic sequences. The seismic response parameters that are mainly examined are the maximum horizontal floor displacement, the maximum floor acceleration, and the distribution of plastic hinges under these historical earthquakes.

3.1. Regular Fixed-Based Mixed Frames under Multiple Earthquakes

As shown in Figures 10 and 11, examining the three- and four-story regular mixed frames, respectively, the maximum horizontal displacements and total floor accelerations under multiple seismic motions are greater in comparison with the single seismic events.

In this subsection, the frames are considered to be fixed. The three-story frame for the case of Mammoth Lakes exhibits a maximum horizontal displacement 0.015 m for the sequential motion and 0.014 m for the most unfavorable single event. For the same case, the floor acceleration for most unfavorable single events and the seismic sequence is 3.4 m/s^2 and 3.8 m/s^2, respectively. The four-story frame for the case of Whittier Narrows exhibits a maximum horizontal displacement 0.05 m for the sequential motion and 0.04 m for the most unfavorable single event, as shown in Figure 11. In the same case, the floor acceleration for the most unfavorable single event and the seismic sequence are the same and equal to 2.9 m/s^2. Figure 12 depicts the formation of plastic hinges of the three-story regular mixed frames under the Coalinga earthquakes. It is obvious that the distribution of plastic hinges for each single seismic event is different in comparison with the distribution of plastic hinges, which corresponds to the seismic sequence.

Finally, Figure 13 displays the time history of horizontal displacement of the central joint at the top of the frame. It is evident that the multiplicity of earthquakes has an influence in the permanent displacements.

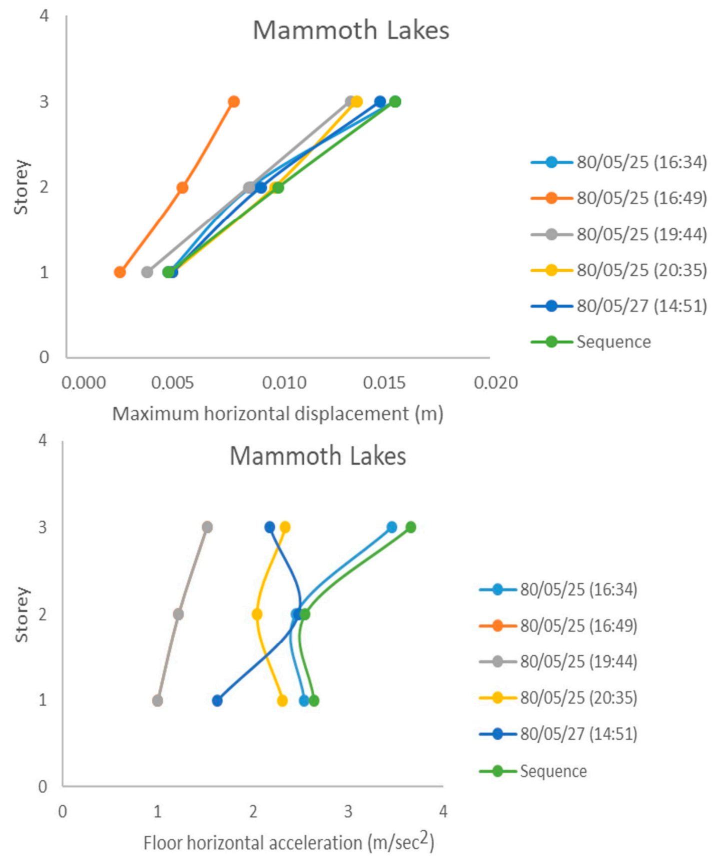

Figure 10. Maximum horizontal displacement and floor acceleration for the three-story regular frame.

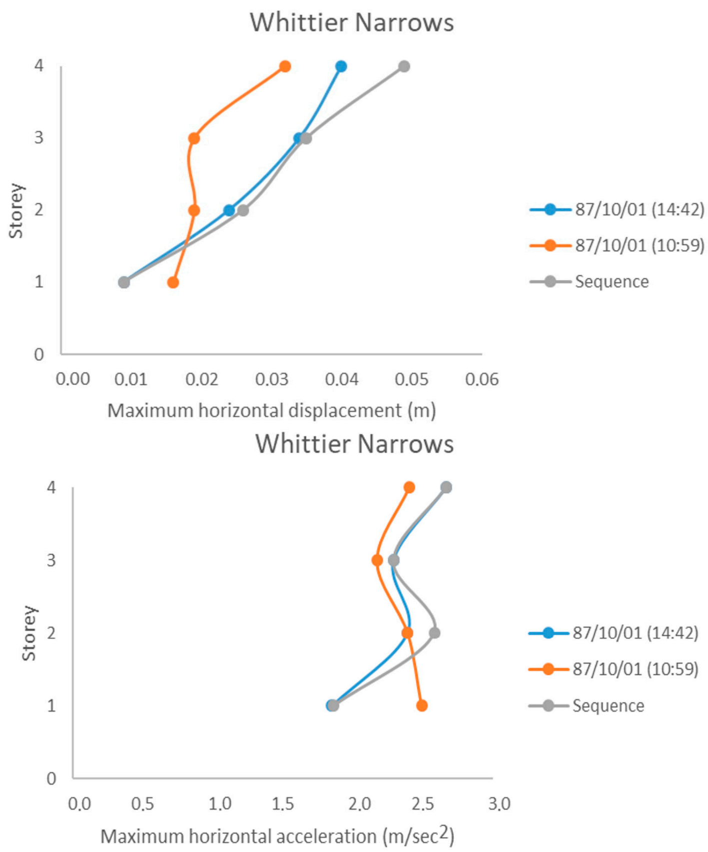

Figure 11. Maximum horizontal displacement and floor acceleration for the four-story regular frame.

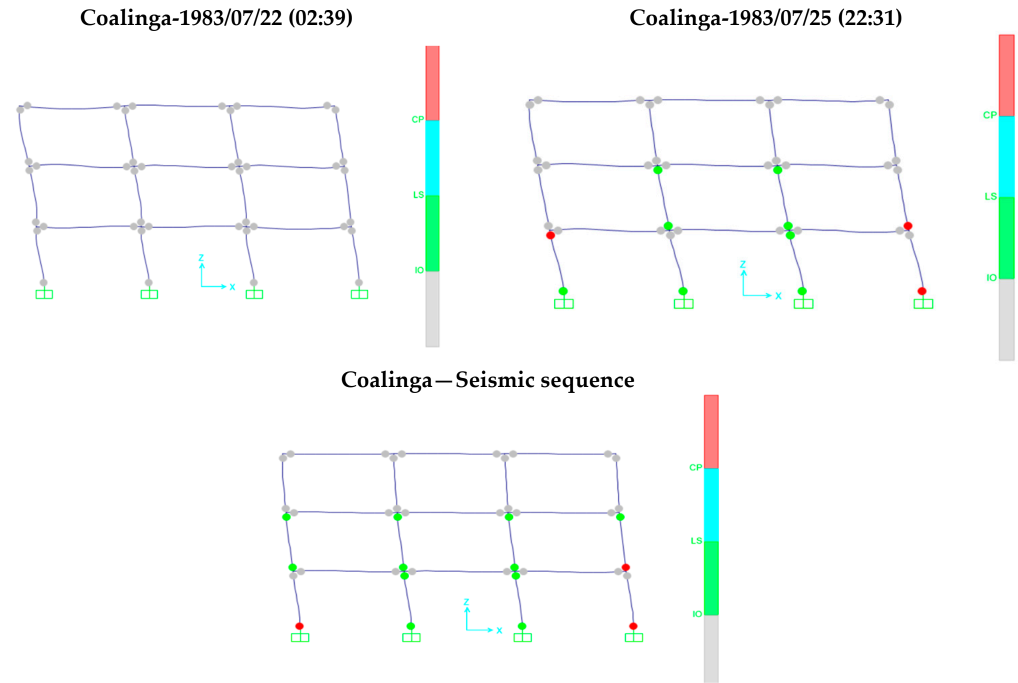

Figure 12. Plastic hinge formation for three-story regular frame under Coalinga earthquakes.

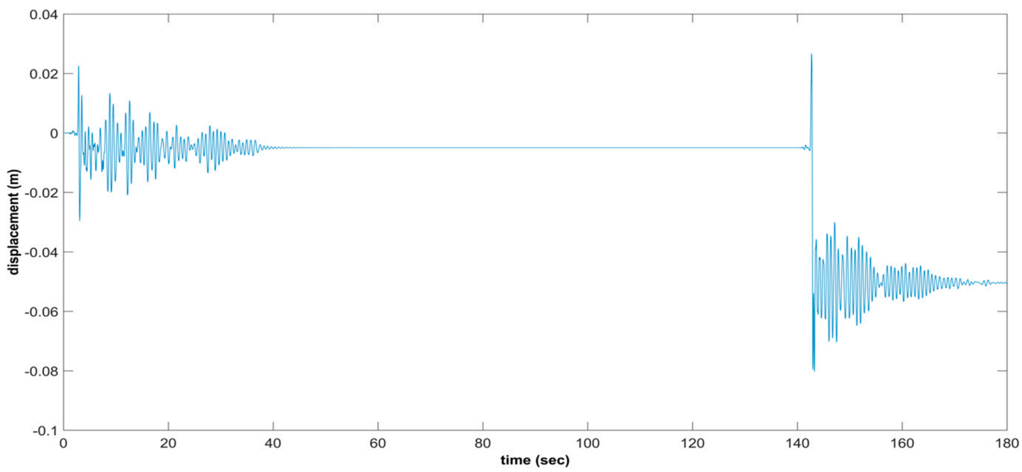

Figure 13. Time−history of horizontal top displacement for three-story regular frame.

3.2. Regular Mixed Frames Based on Flexible Soil under Multiple Earthquakes

This subsection examines the seismic inelastic behavior of the three- and four-story regular mixed frames, taking into account the SSI effects. Figures 14 and 15 examines the effects of multiple earthquakes on the maximum displacement and horizontal acceleration for these frames. More specifically, the three-story frame for the case of Coalinga earthquakes exhibits a maximum horizontal displacement of 0.0157 m for the sequential motion and 0.0172 m for one single event. For the same case, the floor acceleration for one event and the sequence, was 2.9 m/s^2 and 3.1 m/s^2, respectively. The four-story frame for the case of Imperial Valley exhibits maximum horizontal displacement 0.058 m for the sequential motion and 0.048 m for one single event. For the same case, the floor acceleration for one event and the sequence, was the same and equal to 12.0 m/s^2.

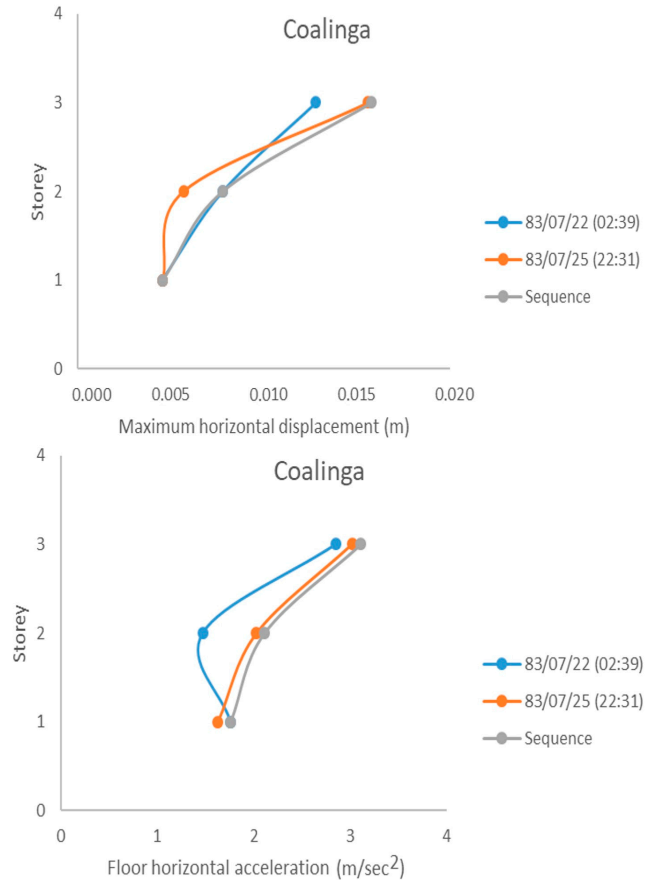

Figure 14. Maximum horizontal displacement and acceleration (three-story frame).

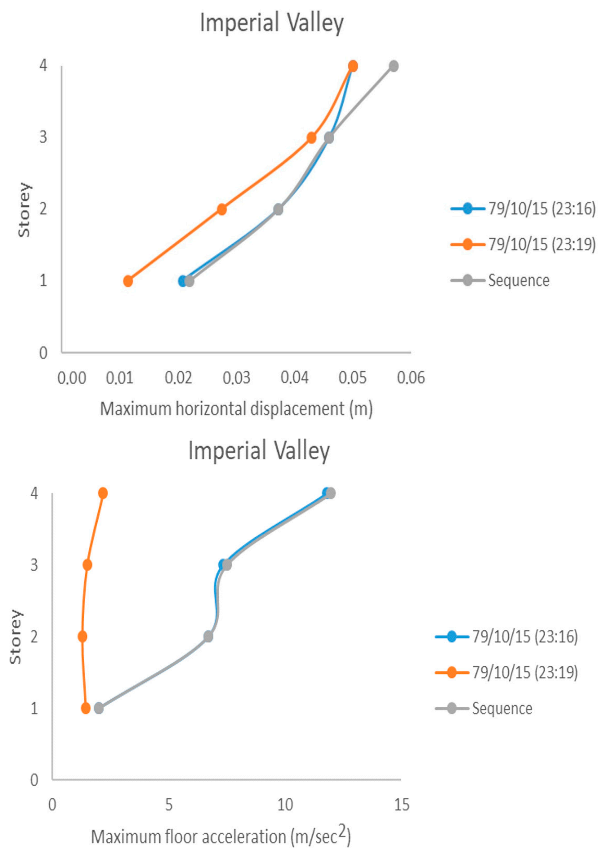

Figure 15. Maximum horizontal displacement and acceleration (four-story frame).

Figure 16 depicts the formation of plastic hinges of the four-story regular mixed frame. It is obvious that the distribution of plastic hinges for each single seismic event is different in comparison with the distribution of plastic hinges, which corresponds to the seismic sequence. Figure 17 shows the time history of horizontal displacement of the central joint at the top of the structure. It is obvious that seismic sequences affect the nonlinear dynamic response behavior of the mixed frames and, more specifically, the permanent displacements. This phenomenon appears in both cases of rigid and compliant soil.

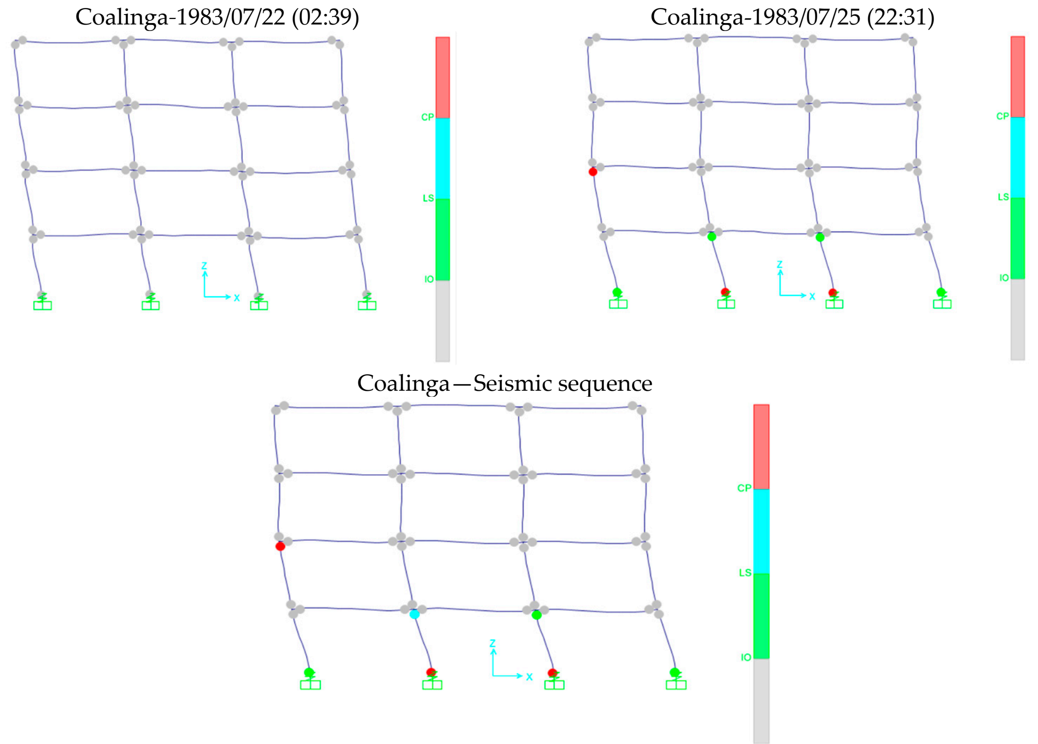

Figure 16. Plastic hinge formation for four-story regular frame under Coalinga earthquakes.

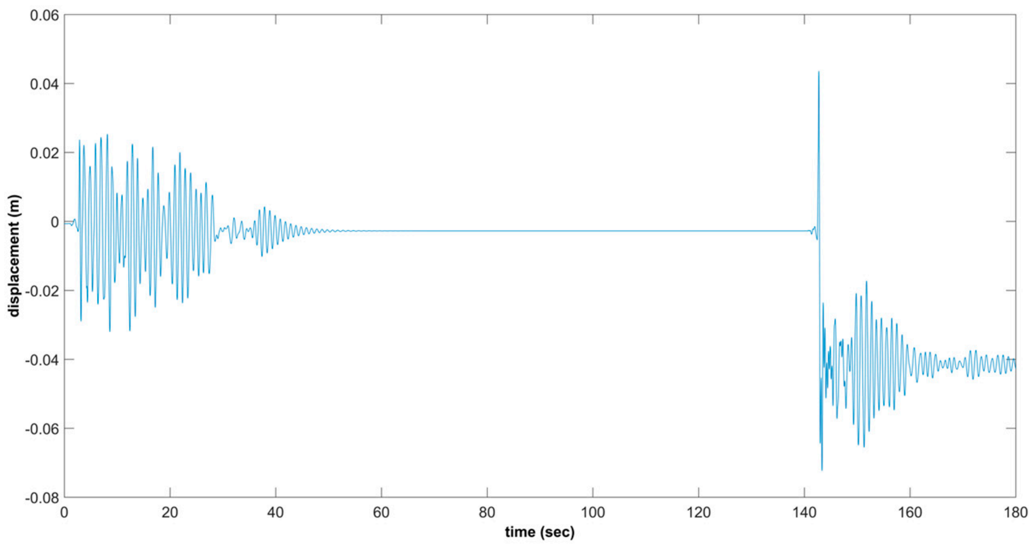

Figure 17. Time–history of horizontal top displacement for four-story regular frame.

3.3. Regular and Irregular Mixed Frames under Multiple Earthquakes

The direction of the earthquake can significantly affect the response of structures. In this study, the irregular structures were subjected to the seismic sequences considering two angles of seismic incidence, 0° and 180°, to examine the influence of the polarity of earthquakes on the structural response. In this case, it seems rational to focus on the seismic behavior of irregular frames.

Figure 18 depicts the distribution of plastic hinges under the sequential motions for angles of incidence 0° and 180°, respectively. It is revealed that the direction of the earthquake influences the response of irregular structures. It is observed that the formation of plastic hinges is completely different. The multiplicity of earthquakes also affects the residual deformation of irregular structures. This fact can be evident from the time history of the displacement of the central joint at the top of the irregular four-story structure, as shown in Figure 19.

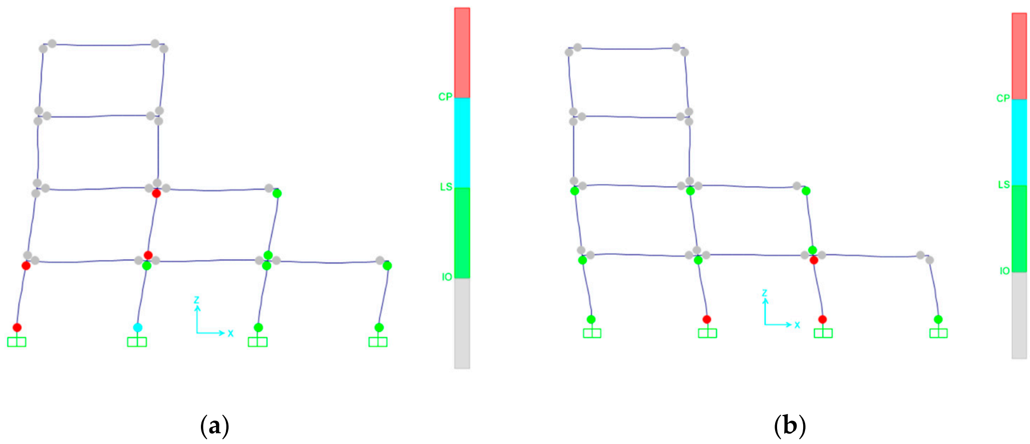

Figure 18. Plastic hinge formation for four-story irregular frame under Coalinga earthquakes. Influence of angle of seismic incidence: (**a**) 0° and (**b**) 180°.

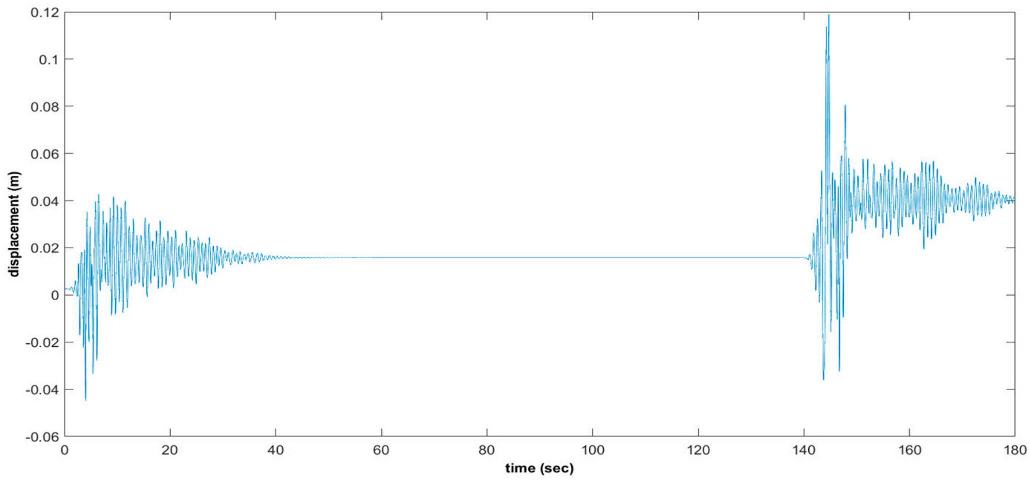

Figure 19. Time−history of horizontal top displacement for the four-story irregular frame.

Finally, it should be mentioned that the accumulation of damages due to the multiplicity of earthquakes can also be affected by some modeling issues such as member damage capacities (e.g., see ref. [31]), plastic hinge length, and effective stiffness of members, etc.

4. Behavior of Mixed Frames under Far-Fault Earthquakes: Selected Results

In this section, the nonlinear behavior of mixed concrete/steel structures is assessed by means of nonlinear time-history (NLTH) analyses employing 20 far-fault seismic records. The seismic response parameters that were mainly examined are the maximum horizontal floor displacement, the maximum floor acceleration, and the distribution of plastic hinges under these seismic records.

4.1. Comparison of Mixed Frames Based on Stiff and Flexible Soil under Far Fault Earthquakes

This section examines the influence of soil flexibility on the behavior of mixed concrete/steel frames subjected to 20 far-fault earthquakes. The analysis focuses on the following parameters: maximum interstory drift ratios, maximum floor acceleration and maximum floor displacements. According to SEAOC [40] and Sozen [41], IDR values about 1% leads to damage of non-structural elements (e.g., infill-walls), whereas IDR greater that 4% leads into non-repairable damage or collapse. Furthermore, it is well known that when designing a structure, the effect of non-structural components is not considered. According to Mohsenian et al. [42], severe damage to non-structural elements can provoke disruption of the serviceability of the structure where one of the most effective method to avoid this damage is the application of viscous dampers [43]. This result indicates that the evaluation of the peak floor acceleration is crucial for the structural design. That is the reason that in this study the acceleration is one important parameter of the seismic response of the frames.

Figure 20 depicts the aforementioned crucial structural parameters for the case of regular mixed structure, where the mean values for the whole set of 20 earthquakes are presented. This figure makes clear the differences between rigid soil assumption and flexible soil consideration. Thus, for the three-story fixed- based mixed structure, the maximum horizontal acceleration is 3.88 m/s^2, the interstory drift ratio is 0.60% and the maximum displacement is 0.0474 m. On the other hand, for the case of deformable soil, the horizontal acceleration (Peak Floor Acceleration: PFA), the interstory drift ratio and the maximum displacement (relative to the ground/zero level) are 3.42 m/s^2, 0.56% and 0,04 m, respectively. It can be concluded that for the three-story mixed frame founded on stiff soil, the maximum floor accelerations, the interstory drift ratio and the maximum displacement is higher in comparison with frames founded on deformable soil.

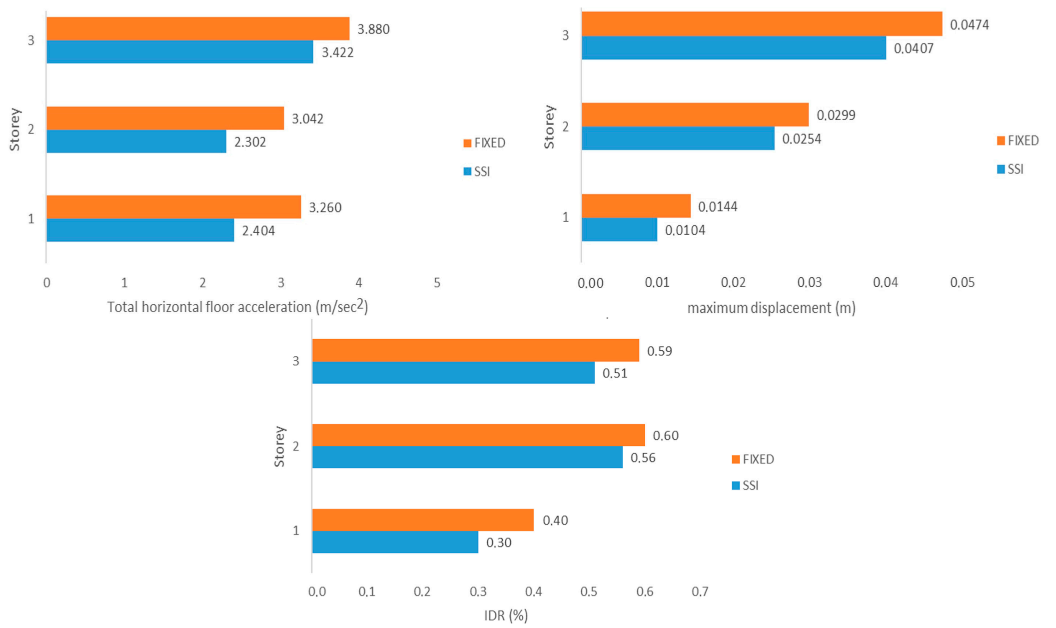

Figure 20. Comparison of floor acceleration, maximum displacement and IDR for structures founded on rigid and deformable soil: three-story regular mixed frame.

In the case of four story mixed frames the total horizontal acceleration, the interstory drift ratio have similar values considering either fixed either on compliant base structures. In the case of three story frames the values of maximum horizontal acceleration, interstory drift ratio and maximum horizontal displacement are higher than the corresponding of four story frames.

From Figure 21, it can be observed that for the four-story fixed based mixed structure, the total horizontal acceleration is 0.972 m/s^2, the interstory drift ratio is 0.188% and the maximum displacement is 0.0139 m. For the case of deformable soil, i.e., taking into account SSI phenomena, the horizontal acceleration (Peak Floor Acceleration: PFA), the interstory drift ratio and the maximum displacement (relative to the ground/zero level) are 0.97 m/s^2, 0.16% and 0.0127 m, respectively. Therefore, it can be observed that for the four-story mixed frame founded on rigid soil, the interstory drift ratio and the maximum displacement are higher in comparison with those for mixed frame founded on deformable soil.

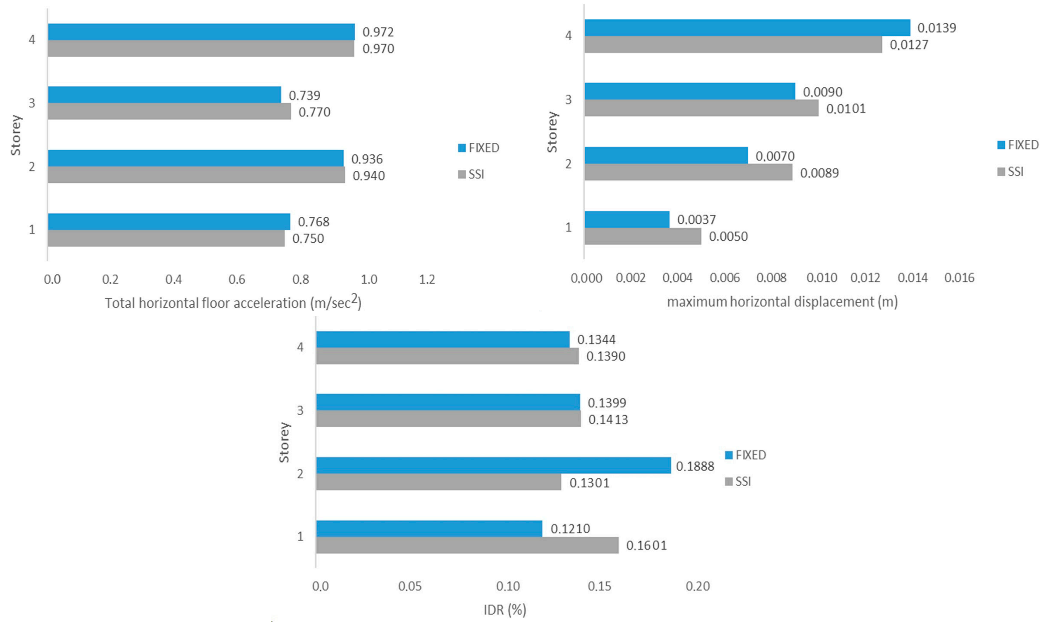

Figure 21. Comparison of floor acceleration, maximum displacement and IDR for structures founded on rigid and deformable soil: four-story regular mixed frame.

A summary of the results for structures founded on rigid and deformable soil is presented in Table 4. As failure is considered here, the case when a member of the structure exhibits plastic hinge that corresponds to the Collapse Prevention earthquake level [31]. Referring to the Table 4, the number of failures for rigid soil are 2 out of 20 cases and for deformable soil are 1 out of 20 cases.

Table 4. Number of failures, IDR, PFA and maximum displacement.

Number of Stories	Number of Failures	Type	IDR (%)	PFA (m/s^2)	Maximum Displacement (m)
3	2/20	Fixed	0.6000	3.888	0.0474
3	1/20	SSI	0.5600	3.422	0.0407
4	1/20	Fixed	0.1888	0.972	0.0139
4	2/20	SSI	0.1601	0.970	0.0127

4.2. Comparison of Regular and Irregular Mixed Frames under Far-Fault Earthquakes

This section focuses on the maximum interstory drift ratios, the maximum floor acceleration and the maximum floor displacements to compare the seismic behavior of regular and irregular structures. The maximum floor acceleration of the irregular frames was 3.61 m/s^2, whereas for regular frames was 3.42 m/s^2. Figure 22 depicts interstory drift ratios and maximum floor displacements for the three-story frames. The maximum value of IDR was 0.56% for the regular and 0.51% for the irregular structures and the maximum displacement was 0.0407 m and 0.0159 m, respectively.

Examining the four-story frames, it is obvious from Figure 23 that the values of maximum horizontal floor acceleration of regular frames are different from the corresponding ones of irregular frames. The peak floor acceleration (PFA) is 0.97 m/s^2 for regular and

2.01 m/s^2 for irregular. Regarding the values of interstory drift ratio and maximum floor displacement, it is clear that the two types of frames exhibit different seismic behavior. The maximum value of IDR was 0.16% for the regular and 0.22% for the irregular structures and the maximum displacement was 0.0127 m and 0.0121 m, respectively. A summary of the results is presented in Table 5 where it is assumed that the failure is materialized when a member of the structure exhibits plastic hinge that corresponds to the collapse prevention earthquake level [31]. Referring to the Table 5, the number of failures for regular and irregular frames are similar (2 out of 20 cases). Finally, it should be mentioned that the noteworthy increasing of floor accelerations, especially at the roof level, is not just related to mixed framed structures but has also been recently acknowledged for other structural systems [44,45].

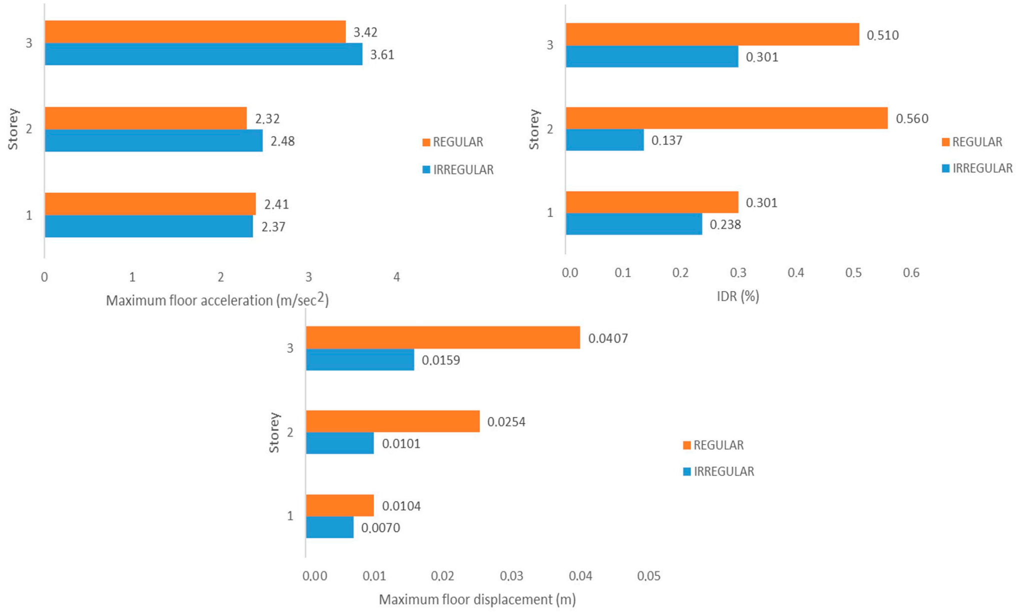

Figure 22. Comparison of floor acceleration, maximum displacement, and IDR for regular and irregular three-story mixed frames.

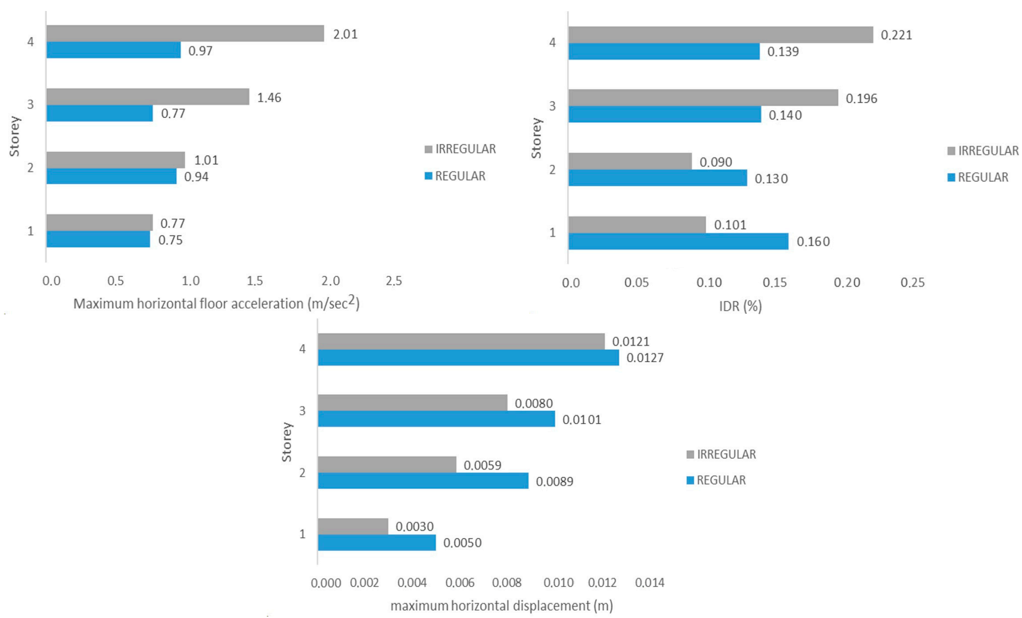

Figure 23. Comparison of floor acceleration, maximum displacement, and IDR for regular and irregular four-story mixed frames.

Table 5. Number of failures, IDR, PFA, and maximum displacement.

Number of Stories	Number of Failures	Type	IDR (%)	PFA (m/s^2)	Maximum Displacement (m)
3	2/20	Regular	0.56	3.61	0.0401
3	2/20	Irregular	0.51	3.42	0.0159
4	2/20	Regular	0.16	0.97	0.0127
4	2/20	Irregular	0.22	2.01	0.0121

5. Discussion and Conclusions

It is important to highlight that the seismic response of mixed concrete-steel frames is affected by the damping ratio assigned to the first few significant modes of vibration. However, the adopted value of viscous damping ratio 4% is within the commonly used values of 3% and 5% for steel and reinforced concrete, respectively, will not significantly alter the conclusions drawn from seismic analyses conducted for this investigation. Furthermore, the results of this research represent the seismic performance of mixed concrete-steel buildings with asymmetrical configurations along their height. With the increasing popularity of mixed construction using different materials in the field of engineering, it is suggested that future versions of seismic codes should incorporate specific seismic design guidelines for vertically mixed concrete-steel structures.

In this paper, the inelastic behavior of mixed concrete/steel structures is assessed by means of nonlinear time-history analyses employing 20 seismic far-fault earthquake motions recorded and five real (as recorded) seismic sequences. The seismic response parameters that examined here are the interstory drift ratio, the peak floor acceleration, as well as the plastic hinge formations.

This research focuses also in the soil–structure interaction effects and the irregularity of structures. Detailed investigation of the problem reveals that:

- The fundamental periods of mixed structures founded on rigid soil is less that the corresponding founded on compliant soil. Thus, soil–structure interaction leads to increased periods in the case of mixed structures;
- Soil–structure interaction leads to lower values of IDR, maximum horizontal displacement and acceleration in the case of three-story frames and to similar values in the case of four-story mixed structures;
- Regular and irregular mixed planar frames exhibit different seismic response. More specifically, the total floor acceleration of the irregular four story frames are two times greater than them of regular;
- Sequential ground motions lead to increased displacement demands in comparison with single events and this parameter must be taken into account by recent provisions;
- Seismic sequences, affect the permanent displacements of structures with different materials. This phenomenon appears in both case of rigid and deformable soil, for both regular and irregular mixed frames.

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