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Safety and Performance of Offshore Platforms Subjected to Repeated Earthquakes

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Abstract: In this work, a systematic study is conducted on the behavior of three-dimensional offshore oil/natural gas platforms under the action of seismic sequences. Such repeated earthquakes result in a noteworthy accumulation of damage in a platform since, in many cases, any rehabilitation process between any two or more successive ground motions cannot be essentially materialized because of lack of time. Conversely, in the past, the seismic response of offshore platforms has been exclusively investigated for the case of single earthquakes. In this study, two three-dimensional platforms are examined, where the first one is assumed to be completely constrained at its base (fixed boundary conditions), while the second one is founded in deformable soil with the aid of long piles. These structures are subjected to real seismic sequences which have been recorded by the same station in a short period of time. Additionally, the platforms under consideration are also subjected to artificial seismic sequences. In this study, we found that sequential earthquakes have a significant effect on the response of these special structures, and this finding should be taken into account in their design.

Keywords: safety and performance of offshore platforms; seismic sequences; dynamic soil–pile–structure interaction

1. Introduction

Strong seismic ground motion is one of the most damaging disasters in nature and may cause severe problems for existing constructions. Taking into account the complicated nature of strong seismic ground motions, as well as their unpredictable incidence time, location, directivity, and severity, engineers have to solve a very difficult problem when they are called to reliably anticipate structural behavior. It should be mentioned that all current seismic codes are based on "design earthquake", i.e., on an isolated and infrequent natural disaster, disregarding the influence of the sequence of earthquakes. Nevertheless, repeated seismic ground motions lead to noteworthy accumulation of structural and non-structural damage, since, in many cases, any rehabilitation procedure between two successive strong ground motions cannot be essentially materialized because of lack of time. Despite the lack of awareness of this phenomenon in the seismic codes, various studies have mentioned and acknowledged the action of seismic sequences, such as those of Hatzigeorgiou and Beskos [1] and Hatzigeorgiou [2–4], where the influence of repeated strong seismic ground motions on the behavior of single-degree-of-freedom (SDOF) systems was comprehensively examined. Additionally, various studies have examined the response of multi-degree-of-freedom (MDOF) systems when they are subjected to repeated earthquakes. One can mention the pioneering work of Fragiacomo et al. [5], which examined steel planar structures under repeated earthquakes. Additionally, Hatzigeorgiou and Liolios [6] and Efraimiadou et al. [7] examined various two-dimensional reinforced concrete structures under sequential earthquakes, while Faisal et al. [8] and Hatzivassiliou and Hatzigeorgiou [9] investigated three-dimensional reinforced concrete framed structures.

Up to the present time, many independent offshore platforms have been constructed in earthquake-prone areas; therefore, investigation of the dynamic behavior of these structures appears to be essential, considering that the seismic failure of them can lead to worker fatality, ecological pollution, equipment destruction, and oil/gas production slowdown. In the past, several papers have been published investigating the safety and performance of offshore platforms under seismic loads, such as the studies of Zayas et al. [10], El Naggar and co-workers [11,12], Kayvani and Barzegar [13], Fisher et al. [14], Peng et al. [15], Asgarian and co-workers [16–19], Bargi et al. [20], Golafshani et al. [21], El-Din and Kim [22], Sharifian et al. [23], Konstandakopoulou et al. [24,25], Wu et al. [26], and Tabeshpour and Fatemi [27]. It should be mentioned that all these works exclusively examined single seismic records, while, to the best of the authors' knowledge, there is no pertinent work that has examined the behavior of offshore platforms under the action of repeated earthquakes. Thus, the need for study of the inelastic seismic response of three-dimensional offshore structures to sequential ground motions is obvious. This work examines the seismic response of three-dimensional offshore platforms subjected to natural and artificial repeated earthquakes, and useful conclusions are derived from this investigation.

2. Elements of Offshore Engineering and Jacket Offshore Platforms (JOPs)

Offshore platforms are structures that have no access to the shore and may be required to stay in place under any meteorological conditions. Offshore platforms can either be floating or immovable from the seabed [28]. Offshore investigation of oil and gas dates back to the nineteenth century. The primary offshore oil wells were drilled in the 1980s from amplified wharfs in the waters of the Pacific Sea, at Offshore Summerlands in California (and Offshore Baku in Azerbaijan, in the Caspian Sea). Be that as it may, the birth of the offshore industry is commonly considered to be in 1947, when Kerr-McGee completed the first fruitful offshore well in the Inlet of Mexico, in 15 ft (4.6 m) deep water off Louisiana. Since the establishment of this initial platform over 70 years ago, and with the exhaustion of coastal and offshore shallow water reserves, the investigation and generation of oil in deep waters has become a challenge to offshore industry. In fact, in 1995, 30% of the world's total oil generation came from offshore sources, whereas modern oil and gas areas are persistently found in progressively more deep waters, including ultra-deep waters. Many of these areas are small and can provide generation with the existing innovations.

To date, an incredible number of offshore structures have been introduced around the world. In spite of the fact that most of them have withstood the test of time, there have also been a few disastrous mishaps and failures throughout the years. Climate, blowout, capsizing, and human error have brought about wounds, fatalities, basic failures, and considerable financial troubles.

There are different sorts of offshore platforms for oil and gas investigation, where the foremost fitting sort is inferior in terms of applications as well as the depth of seawater. The majority of offshore structures have been built in shallow waters, e.g., up to 500 m, of the terrain rack, where approximately 95% or more of them around the world are jacket built, which can be settled specifically to the seabed. These offshore structures are completely tied down on the seabed, and their beat deck is supported by a steel tubular outline; this 3-D surrounded structure is called the jacket. The fundamental auxiliary components of a jacket offshore platform (JOP) are the deck, jacket, and piles. The jacket acts as bracing for the establishment components (piles) beneath sidelong loads such as ocean waves, wind, and seismic tremors, whereas the deck is settled upon the jacket. In arrange to control the JOP on the seabed, the surrounding structure is founded on steel piles to guarantee the stability of the entire structure. The entire elevation of the structure is at least the water depth plus the greatest wave height, i.e., the water depth plus 10–15 m. The JOP is designed to maintain different loadings and forces, such as the weight of the generation offices, cranes topside, ocean waves, temperature differences, wind and seismic action, and probable ship- or ice-induced vibrations. Considering the full set of design demands for JOPs, their costs are nearly 35–45% that of the entire structure.

3. Jacket Offshore Platforms under Consideration

Finite element models were constructed using the dynamic analysis program Ruaumoko [29]. This program is based on the concentrated plasticity approach, avoiding more complicated methods such as the fiber modeling of member sections [30]. This nonlinear seismic analysis program is ideal for simulating JOPs, taking into account its capability for evaluating the post-buckling behavior of tubular elements and of pile–soil–platform interaction. A 3-D model was created for the seismic inelastic behavior of JOPs. Thus, inelastic/large-deformation beam-column members, assuming concentrated plasticity behavior, were adopted to simulate the whole set of members for the offshore structure. All members were modeled assuming concentrated plasticity moment–rotation and force–displacement relations with an inelastic-to-elastic ratio equal to 1%. Figures 1 and 2 show the structure under consideration, where the structural design follows the Eurocodes Provisions [31]. More specifically, Figure 1 depicts the offshore platform assuming rigid (undeformable) soil, while Figure 2 shows the structural model that takes into account the soil–pile–platform interaction (i.e., considering soil deformability).

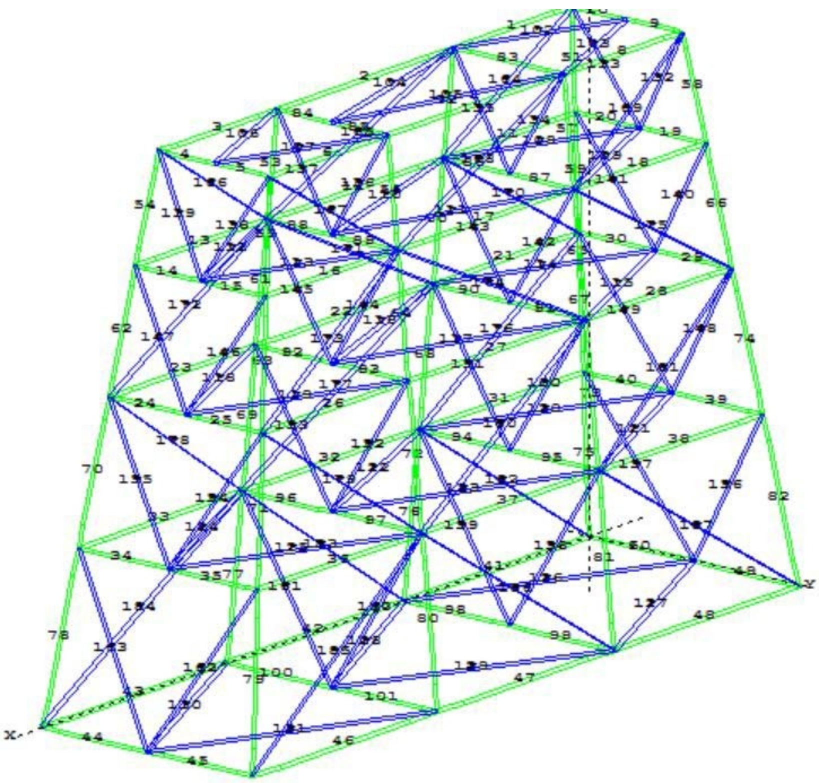

Figure 1. Three-dimensional view of the fixed-base jacket platform.

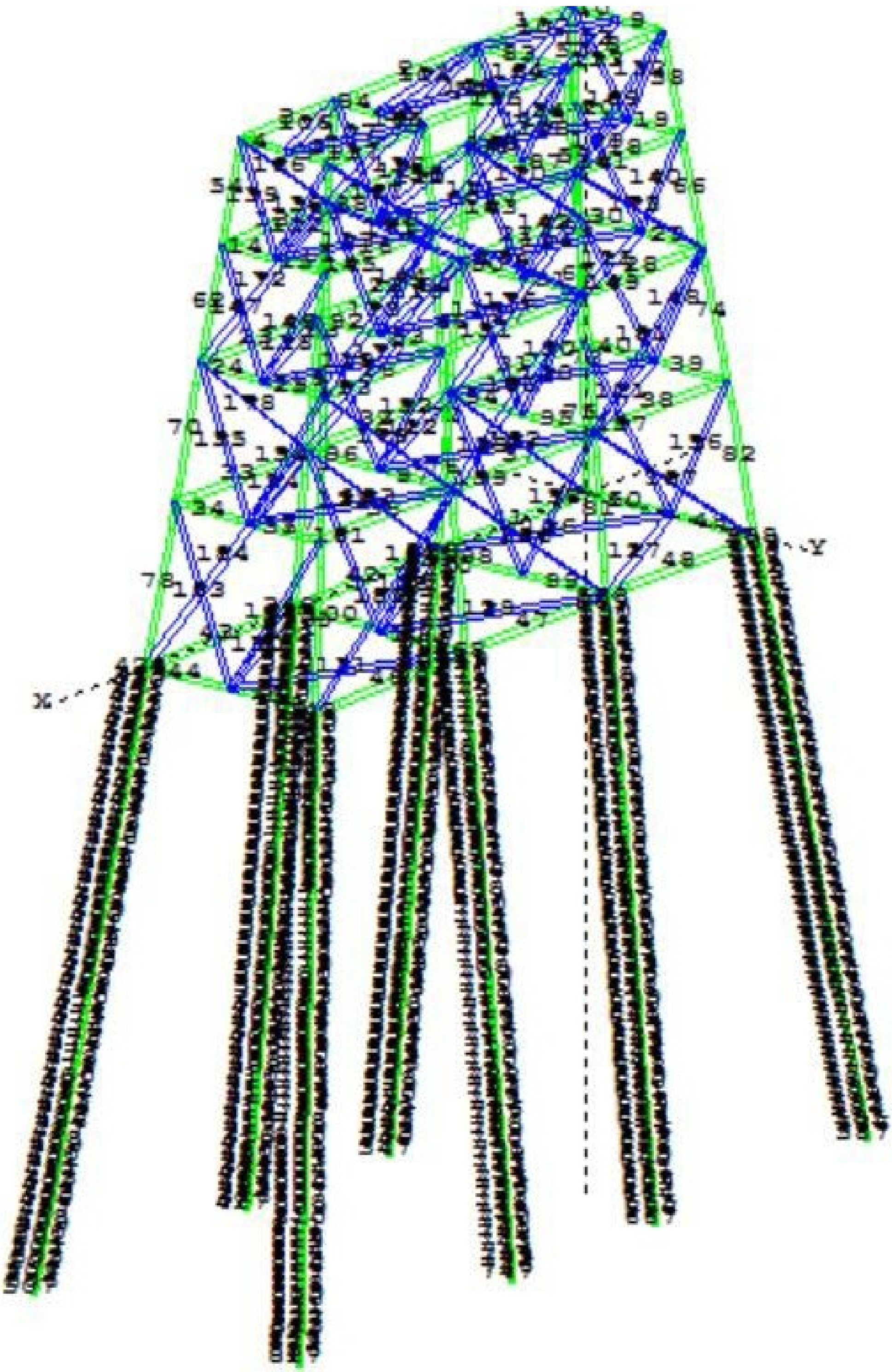

Figure 2. Three-dimensional view of a jacket platform based on deformable soil (soil–pile–platform system).

Each element was modeled as a beam-column member with a circular thin-wall cross section. The data of these members are given in Table 1. All structural members were modeled according to the Al-Bermani hysteresis rule [32], except diagonal braces, which were modeled by the Remennikov–Walpole hysteresis rule [33], all offered in Ruaumoko [29].

Table 1. Cross sections of the platform's tubular members.

Type of Member	Level	Cross Section [Mm]
Braces	0	55.0×2.5
	1	55.0×2.5
	2	60.0×2.2
	3	50.0×2.6
	4	50.0×2.2
Columns	0	110.0×5.0
	1	110.0×5.0
	2	100.0×4.5
	3	90.0×4.0
	4	90.0×4.0
Beams	0	75.0×4.5
	1	75.0×4.5
	2	80.0×4.2
	3	75.0×4.0
	4	50.0×2.5

4. The Phenomenon of Multiple Earthquakes

The seismic design parameters are usually evaluated for the case of infrequent "design earthquake", and the seismic codes have not paid attention to the effect of seismic sequences. Instead of this practice, pertinent recent studies have examined numerous cases of repeated ground motions. For example, Amadio et al. [34] and Hatzigeorgiou et al. [1–4] investigated the influence of seismic sequences on the inelastic behavior of single-degree-of-freedom systems. Additionally, in the last decade, numerous studies have examined the seismic behavior of multi-degree-of-freedom structures, such as tanks [35], planar framed structures [5–7,36], or three-dimensional building structures [8,9]. However, no past work examined the behavior of offshore platforms under repeated earthquakes. Multiple earthquakes can be described as the recurrence of moderate or intense ground motions after small or extensive periods of time. For example, the Coalinga (see Figure 3) earthquake (22 July 1983 at 02:39), an intense ground motion with magnitude $M_L = 6.0$ and peak ground acceleration 0.605g, was followed by an intense aftershock three days later (25 July 1983 at 22:31) with smaller magnitude $M_L = 5.3$ but with larger peak ground acceleration, 0.733g. The response spectra for these records are shown in Figure 4. It is obvious that the response spectrum of the aftershock almost covers that of the mainshock seismic event, and it is nearly the same in terms of the spectrum of the ground motion sequence (22 and 25 July 1983).

Figure 3. Map of earthquakes under consideration.

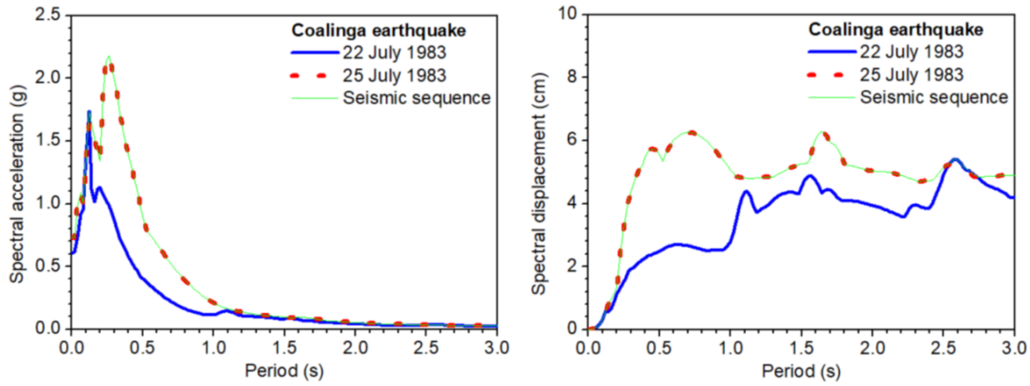

Figure 4. Elastic response spectra for the Coalinga earthquakes: single seismic events and seismic sequence.

It should be mentioned that Figure 4 is a dyad of the acceleration and displacement response spectra for the cases of single earthquakes and for the seismic sequence. Similarly, Figure 5 depicts the constant-ductility-demand acceleration and displacement spectra for these earthquakes, examining the ductility values μ = 6 and μ = 10. It is evident that the spectral acceleration and displacement values for the case of the seismic sequence are greater than or equal to the maximum values of the counterparts for the single events.

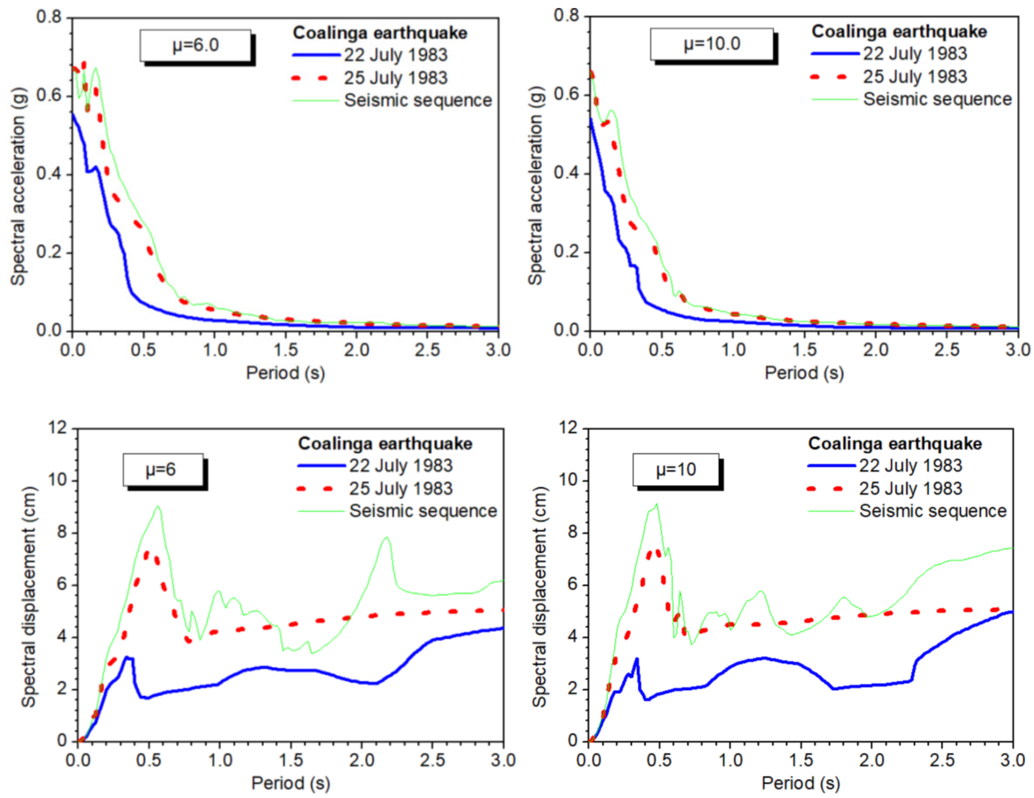

Figure 5. Constant-ductility acceleration and displacement spectra for the Coalinga earthquakes: μ = 6 and μ = 10.

The offshore platforms under consideration were subjected to various seismic sequences. More specifically, five Californian (see Figure 3) multiple earthquakes were used in this study, but any other seismic sequence could be used, considering that the examined platforms could be installed in any seismic-prone area in the world. These repeated earthquakes and their separated single seismic events are shown in Table 2. Furthermore, the acceleration spectra for these seismic sequences appear in Figure 6 (the Coalinga earthquakes were examined in Figure 4).

Table 2. Multiple earthquakes under consideration.

No.	Seismic Sequence	Station	Date (Time)	Magnitude M_L
1	Mammoth Lakes	Convict Creek	1980/05/25 (16:34) 1980/05/25 (16:49) 1980/05/25 (19:44) 1980/05/25 (20:35) 1980/05/27 (14:51)	6.1 6.0 6.1 5.7 6.2
2	Chalfant Valley	Zack Brothers Ranch	1986/07/20 (14:29) 1986/07/21 (14:42)	5.9 6.3
3	Coalinga	46T04 Station	1983/07/22 (02:39) 1983/07/25 (22:31)	6.0 5.3
4	Imperial Valley	Holtville Post Office	1979/10/15 (23:16) 1979/10/15 (23:19)	6.6 5.2
5	Whittier Narrows	San Marino	1987/10/01 (14:42) 1987/10/04 (10:59)	5.9 5.3

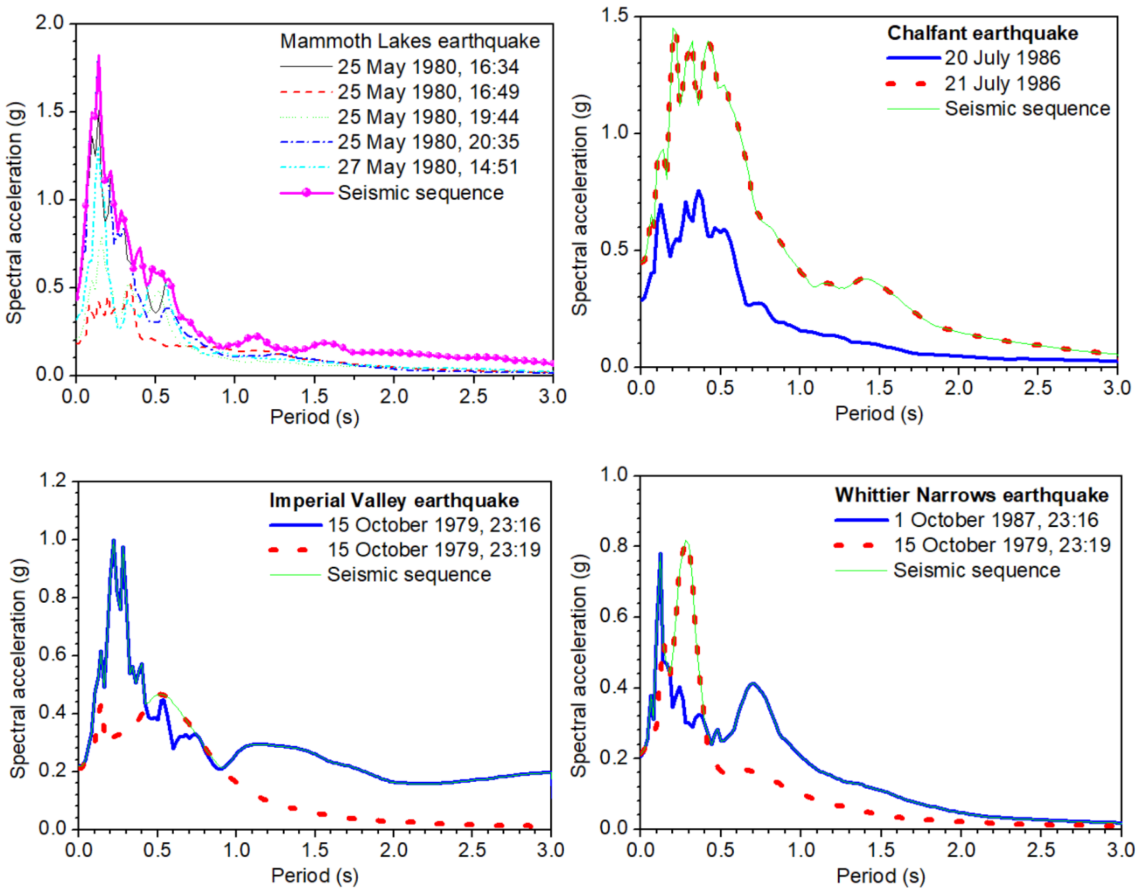

Figure 6. Elastic response spectra of the earthquakes under consideration: single seismic events and seismic sequences.

5. Selected Results

This section provides selected results from the dynamic inelasticity analysis of offshore jacket platforms subjected to repeated earthquakes. More specifically, this section focuses on the most critical structural parameters, such as the top horizontal displacement–base shear diagrams, time history of maximum displacements, and residual displacements. These structural parameters were investigated for both cases, fixed-base platforms and soil–pile–structure hybrid systems.

Figure 7 depicts the response of the soil–pile–platform system under the action of the Mammoth Lakes earthquake (25–27 May 1980). More specifically, this figure shows the top horizontal displacement–base shear diagrams, which are very helpful to evaluating the inelastic behavior of platforms and numerous structural parameters, such as the global hysteretic behavior, the maximum seismic bearing capacity, the initial stiffness of the soil–pile–platform system, the softening behavior, the strength deterioration, and the maximum displacement demands, amongst others. The seismic sequence appears to be the more detrimental case in comparison with the worst case of the separated/single seismic events.

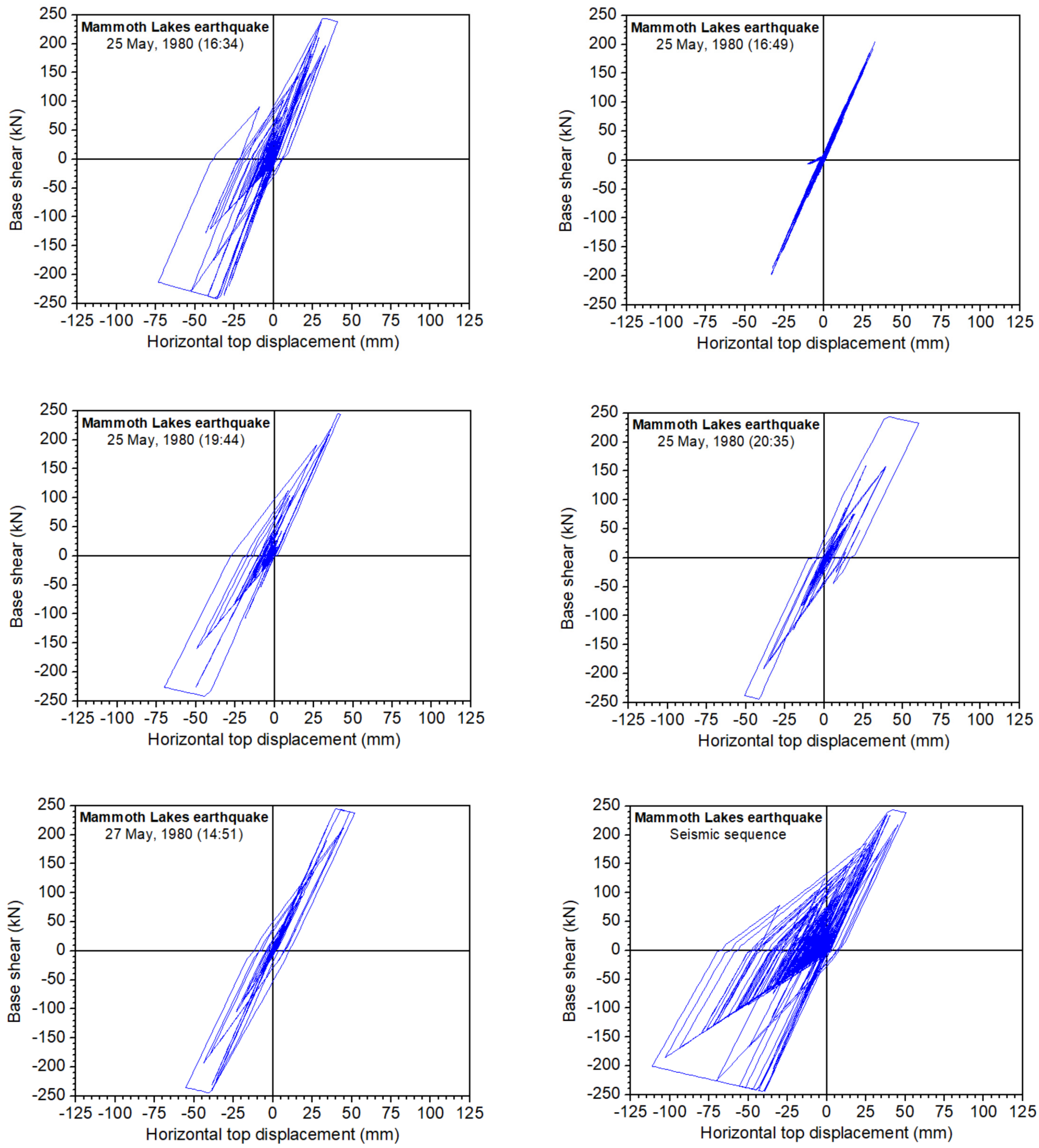

Figure 7. Soil–pile–platform system under the Mammoth Lakes earthquake (25–27 May 1980).

Similar to the above-mentioned case, Figure 8 shows the behavior of the fixed-base jacket platform under the action of the Mammoth Lakes earthquake (25–27 May 1980). It is obvious that the seismic sequence seems to be the more crucial case in comparison with the worst case of the separated particular seismic records. It should be mentioned that there is a noteworthy difference between the behavior of the fixed-based platform and that of the soil–pile–platform counterpart system, which has to do with the more flexible behavior of the latter and with the nonlinearity of the soil medium.

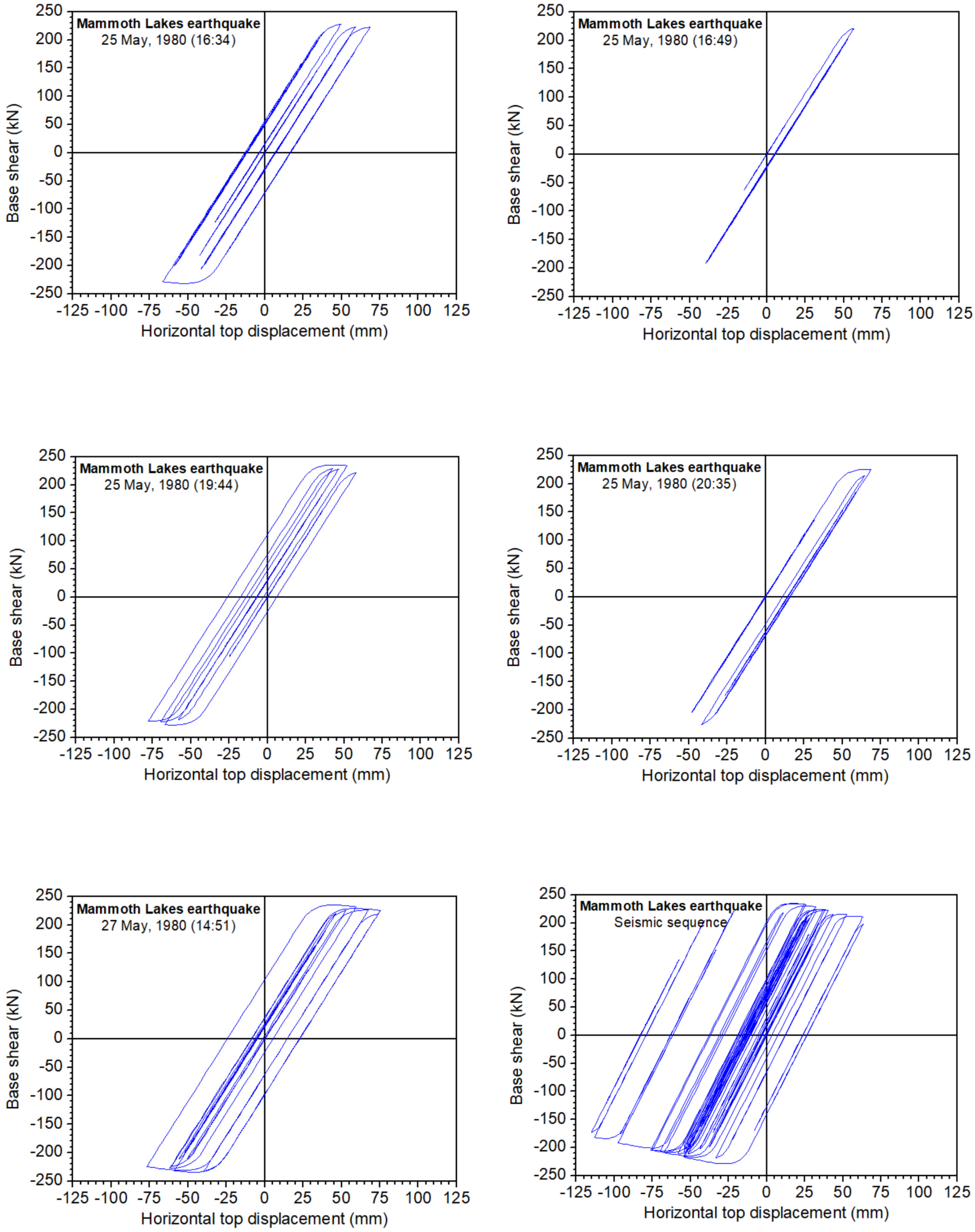

Figure 8. Fixed-base platform under the Mammoth Lakes earthquake (25–27 May 1980).

It is worth noting that behavior similar to that in Figures 7 and 8 is also presented in Figure 9, which shows the soil–pile–platform response under the Chalfant Valley earthquake. It is evident that the seismic sequence leads to more intense results in comparison with the single records. Furthermore, Figure 10 shows the displacement time history for the Chalfant Valley earthquakes. In each case, between the two consecutive seismic events, a time gap of 100 sec (from 40s to 140s) is applied. This gap is characterized by zero ground acceleration ordinates and it is absolutely enough to cease the movement of any structure due to damping and prepare the platform for the next seismic action [6]. It is evident that the residual displacement, which appears at the end of each seismic event, is accumulated.

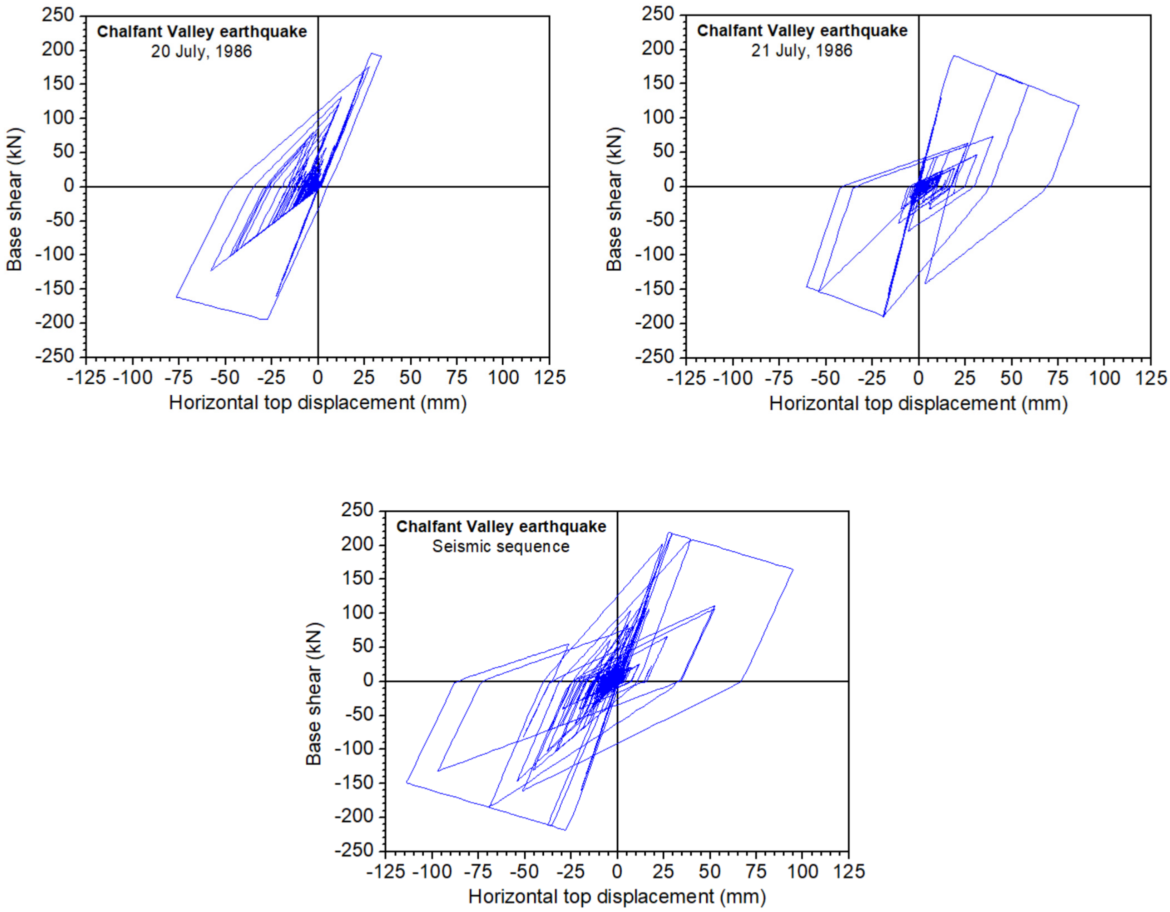

Figure 9. Soil–pile–platform system under the Chalfant Valley earthquake (20–21 July 1986): single seismic events vs. seismic sequence.

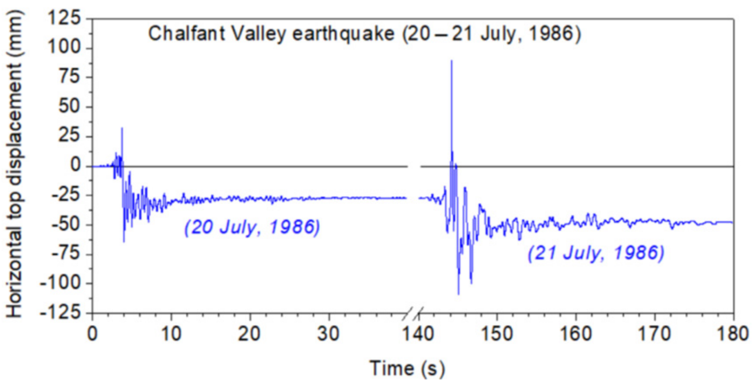

Figure 10. Soil–pile–platform system under the Chalfant Valley earthquake (20–21 July 1986): time history of the horizontal top displacement.

The seismic sequence of the Coalinga earthquake (22–25 July 1983) is examined in the following. More specifically, Figure 11 shows the behavior of a fixed-base platform under the action of the Coalinga earthquake (20–21 July 1986). It is obvious that the seismic sequence leads to more intense results in comparison with the separated single earthquakes.

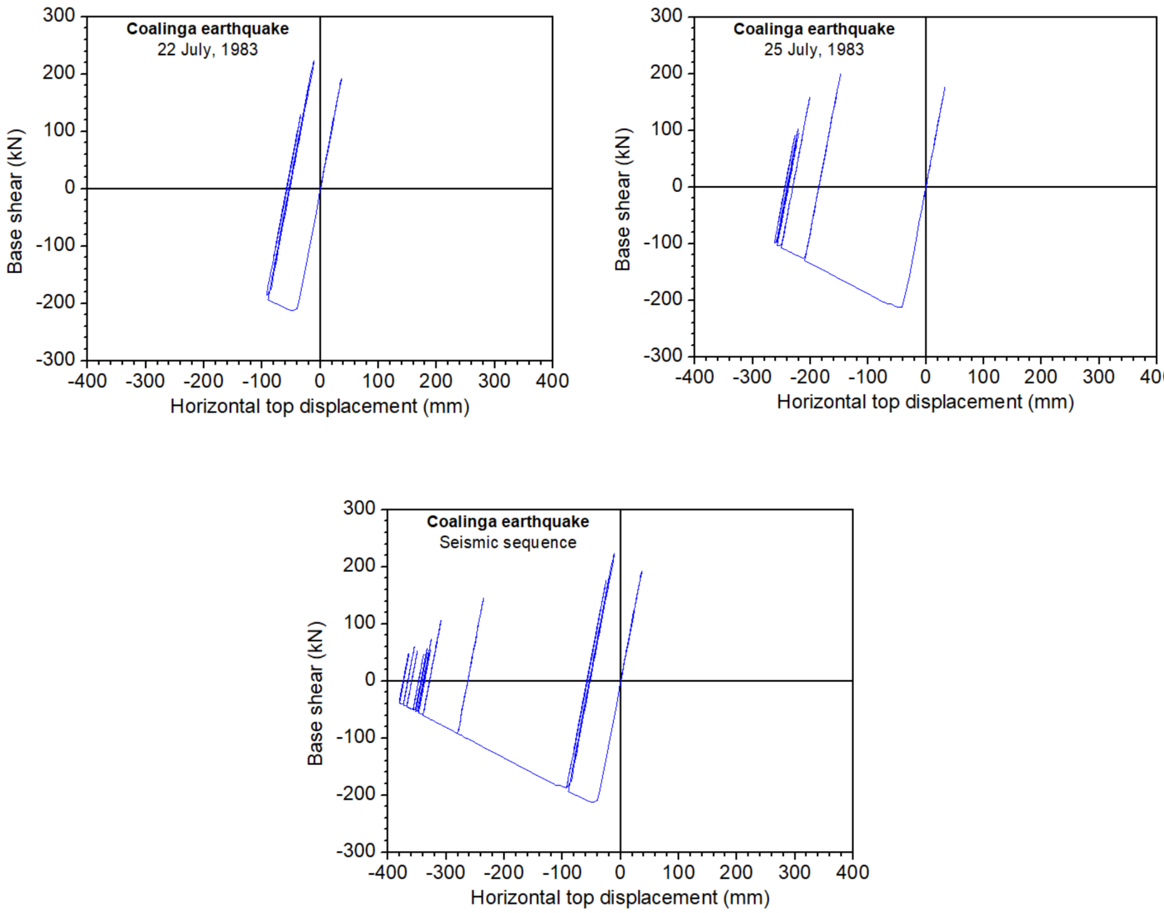

Figure 11. Fixed-base platform under the Coalinga earthquake (22 and 25 July 1983): single seismic events vs. seismic sequence.

Additionally, Figure 12 depicts the time history of the top horizontal displacement for the case of the Coalinga seismic sequence. It should be mentioned that the residual displacement, which appears at the end of each seismic event, is accumulated.

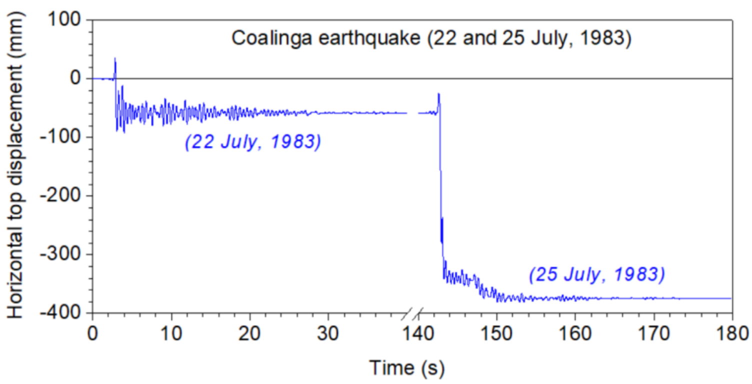

Figure 12. Fixed-base platform under the Coalinga earthquake (22 and 25 July 1983): time history of horizontal top displacement.

The seismic sequence of Imperial Valley (15 October 1979) is examined next. Specifically, Figure 13 depicts the behavior of the fixed-base platform under the action of the Imperial Valley earthquake (15

October 1979, 23:16 and 23:19). It is obvious that the seismic sequence leads to more intense results in comparison with the separated single earthquakes.

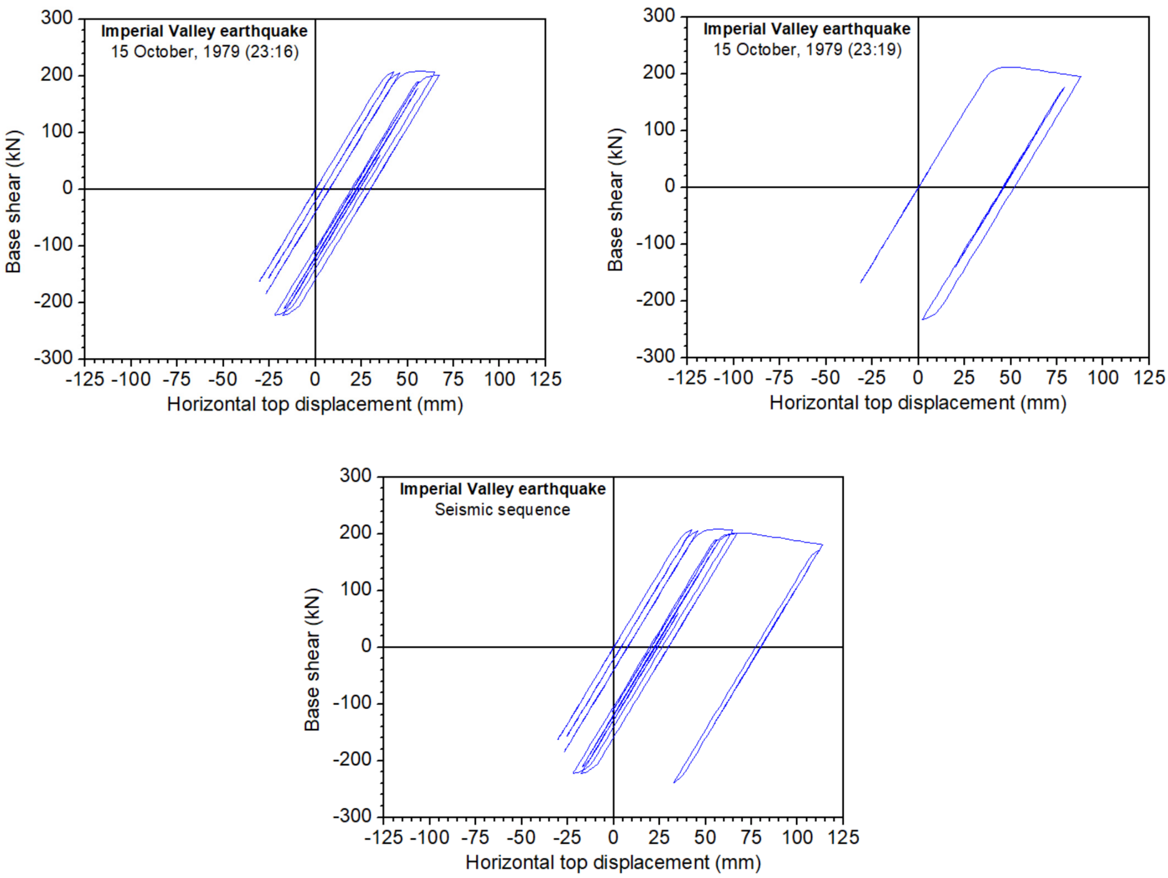

Figure 13. Fixed-base platform under the Imperial Valley earthquake (15 October 1979, 23:16~23:19): single seismic events vs. seismic sequence.

Moreover, Figure 14 depicts the time history of the top horizontal displacement for the case of the Imperial Valley seismic sequence. It is evident that the residual displacement, which appears at the end of each seismic event, is accumulated.

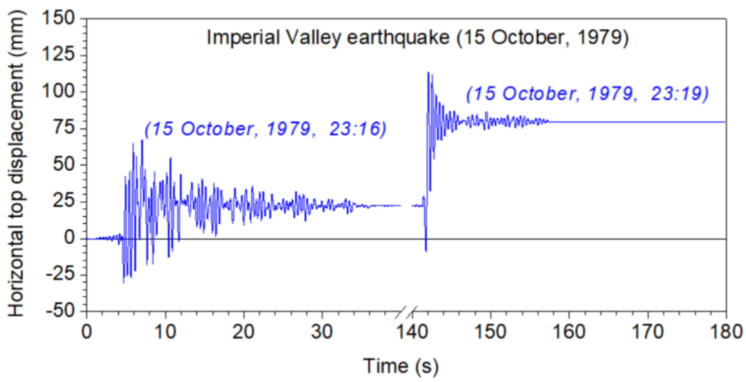

Figure 14. Fixed-base platform under the Imperial Valley earthquakes (15 October 1979, 23:16~23:19): time history of the horizontal top displacement.

Finally, the seismic sequence of the Whittier Narrows earthquake (1–4 October 1987) is investigated in the following. More specifically, the nonlinear dynamic response of a fixed-base platform under the action of the Whittier Narrows seismic sequence is shown in Figure 15. It can be concluded that the seismic sequence leads to more intense results in comparison with the separated single earthquakes.

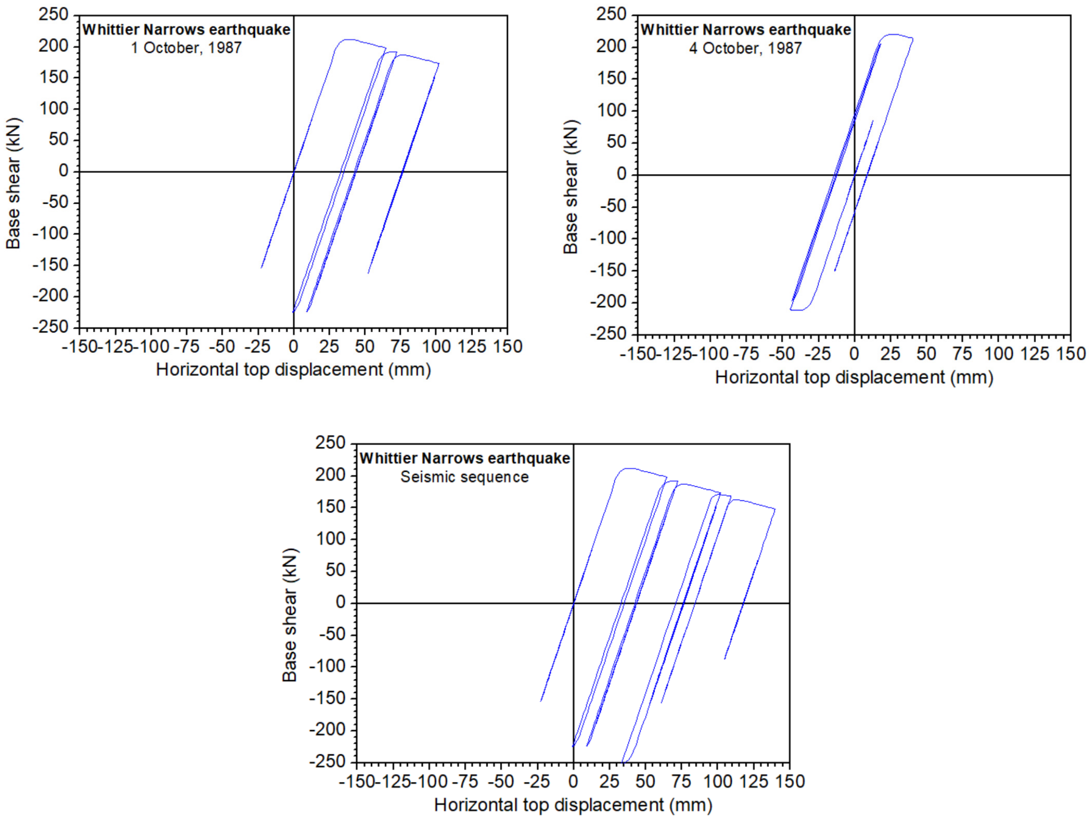

Figure 15. Fixed-base platform under the Whittier Narrows earthquakes (1–4 October 1987): single seismic events vs. seismic sequence.

Furthermore, the time history of the top horizontal displacement for the case of the Whittier Narrows seismic sequence is given in Figure 16. It was found that the residual displacement, which appears at the end of each seismic event, is accumulated.

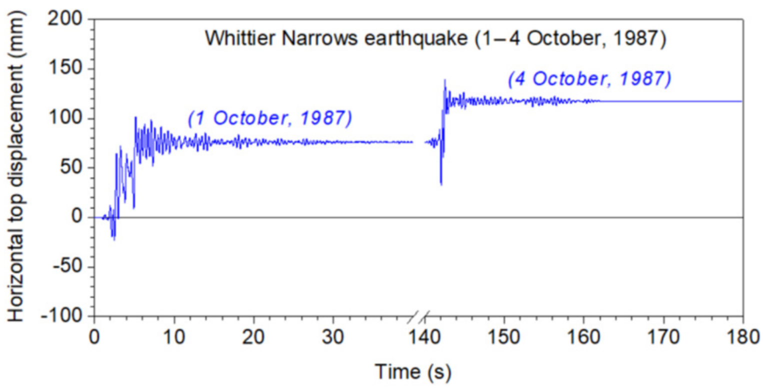

Figure 16. Fixed-base platform under the Whittier Narrows earthquakes (1–4 October 1987): time history of the horizontal top displacement.

It seems to be useful to compare both the maximum and residual displacements between the fixed-base platform and the soil–pile–platform system. Thus, for reasons of comparison and without loss of generality among the cases, Figure 17 depicts the response of the soil–pile–platform system and, more specifically, the time history of the top horizontal displacement for the case of the Imperial

Valley earthquakes. It is obvious that both the maximum and residual displacements are quite different between the fixed-base platform and the soil–pile–structure system.

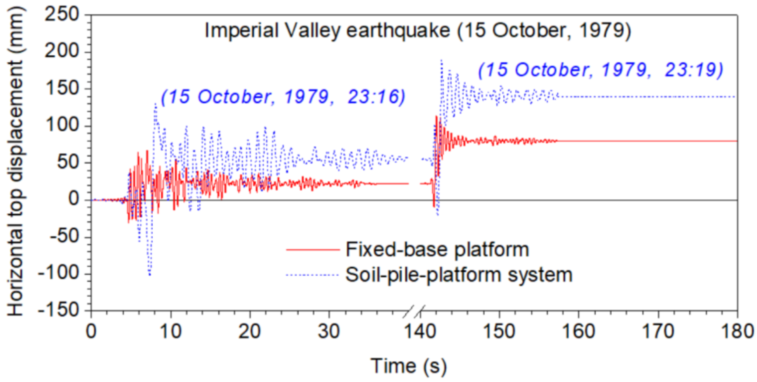

Figure 17. Fixed-base platform vs. soil–pile–platform hybrid system under the Imperial Valley earthquakes (15 October 1979, 23:16~23:19).

It is worth noting that one of the most powerful tools to evaluate the behavior of structures and assess their performance and safety under the action of repeated earthquakes is incremental dynamic analysis (IDA) [37]. Without loss of generality among the cases, Figure 18 depicts the IDA curves for the case of the Imperial Valley seismic sequence (15 October 1979).

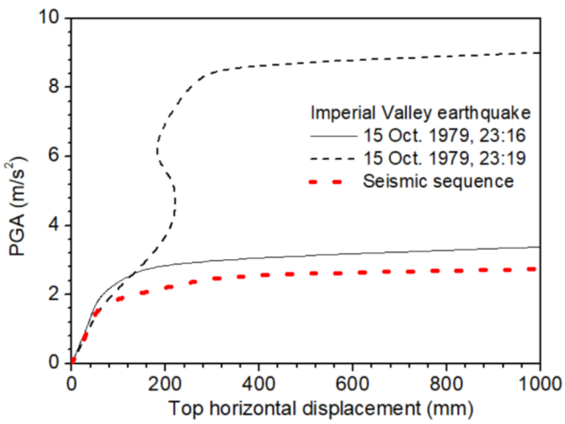

Figure 18. Incremental dynamic analysis curves for the fixed-base platform (in Peak Ground Acceleration – PGA – terms) under the Imperial Valley earthquake (15 October 1979, 23:16 and 23:19): single seismic events vs. seismic sequence.

It was found that the seismic sequences lead to detrimental results in comparison with the cases of separated single earthquakes since specific displacements can be achieved with the former for lower values of Peak Ground Acceleration (PGA), while single earthquakes require higher values of PGA for these displacements.

6. Conclusions

The dynamic inelastic response of three-dimensional oil/gas jacket platforms under multiple strong earthquakes was investigated in this study. Five real—as-recorded—seismic sequences were applied to examine these phenomena in detail. As reported by this study, the following conclusions are highlighted:

1. Multiple earthquakes have increased deformation demands in comparison with separated earthquake records. The maximum top horizontal displacements and permanent deformation

due to multiple strong ground motions appear to be increased in comparison with those due to single earthquakes. This behavior is noteworthy and should be considered during the seismic design of platforms either by traditional force-based design or by displacement-based design approaches, which necessitates a reliable evaluation of deformation demands.

2. The base shear–deformation diagrams for repeated ground motions are different than their counterparts for single earthquakes.
3. The dynamic soil–pile–structure interaction should be taken into account for both the analysis and design of offshore platforms, since their seismic behavior is strongly affected by the flexibility and inelasticity of the soil medium.
4. The incremental dynamic analysis approach was applied in this study and showed that repeated earthquakes lead to higher deformation values than do the corresponding single earthquakes.

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