Safety of Oil/Gas Offshore Platforms Designed According to European Provisions under the Action of Pulse-Like Ground Motions

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Abstract. Oil and gas offshore platforms are important civil constructions, which are loaded by various types of environmental actions such as wave loads and wind forces. These actions usually govern the platforms’ structural design, while seismic action appears to have minor influence. Nonetheless, numerous offshore structures have been founded in earthquake-prone regions where the structural design can be strongly affected by earthquake action. Many studies have investigated the seismic behaviour of oil and gas offshore platforms examining traditional seismic records. This study investigates the application of simple pulses, i.e., exponential, triangular, rectangular and sinusoidal pulse waveforms, as an earthquake excitation for offshore platforms. To the best of the authors’ knowledge, this is the first time that the aforementioned set of simplified ground motions have been applied to assess the nonlinear seismic behaviour of offshore oil/gas platform. It should be mentioned that pulses could make important information concerning the dynamic response available considering that many intense seismic events enclose actually an acceleration pulse, which can lead to a nonlinear structural response. It is worth noticing that a small number of works have examined the nonlinear response of the platform and most of the previous works assumed fixed boundary conditions ignoring the soil-structure interaction. On the contrary, this study investigates the structural response of 3-D platforms under the action of simplified pulses, considering also the soil-pile-platform interaction. It should be mentioned that the structural design of these special structures fulfils the Eurocode 8 standards. Finally, this work investigates the effect of angle of earthquake waves incidence.

1. Introduction

Oil and Gas Offshore Platforms (OGOPs) have been constructed in various sites in the world [1]. Protecting the reliability of OGOPs in seismic prone regions appears to be an important necessity for these special structures. Earlier investigation on OGOPs commonly concentrated on sea-wave and currents’ effects while the investigation on nonlinear earthquake response is rather infrequent. This perhaps endorsed to the fact that the behaviour of OGOPs often mainly affected by non-seismic environmental actions such as wind current and waves. Today, there are more about 7,000 platforms in use across the world where one third of them has been in use for 25 years or more [2]. Numerous of
these OGOPs are used further than their design life and it should be mentioned that in some cases where new oil and gas reservoirs are uncovered, the process life of the active platforms should be expanded. Especially for the case of OGOPs founded in seismic-prone locations, the stability and strength of the special constructions have been studied in-depth, especially in the last five years by numerous researchers [3-10]. It is worth noticing that for the most of the cases, the seismic analysis of offshore platforms focuses on the traditional far-field ground motion while a few studies have examined the behaviour of OGOPs under near-fault earthquakes (e.g., [7]). Near-fault earthquakes are characterized by specific pulses [11-13]. For this reason, many researchers have investigated pulses for the earthquake analysis of structures such as in Ref. [14] where sinusoidal pulses are adopted to simulate the behaviour of ground surface near canyons using various ground and shapes conditions. Additionally, in [15] the seismic behaviour of nuclear power plants was investigated applying sinusoidal pulses. However, to the best of the authors’ knowledge, such simple pulses for the simulation of strong ground motions to investigate the nonlinear response of offshore platforms have been not investigated yet. This paper examines for the first time the inelastic behaviour of offshore platforms under the action of simple pulses (i.e., sinusoidal, triangular, rectangular and exponential pulse waveforms) correspond to intense ground motions. Two different models are investigated where the first model considers the dynamic pile-soil-structure interaction and the second model considers that the soil is undeformed. This study concentrates on the earthquake performance of OGOPs investigating the maximum displacements and accelerations. Additionally, the maximum forces/moments for critical members are also examined, both for flexible and rigid soil. Finally, this study provided helpful conclusions and ideas for forthcoming investigations.

2. Simplified pulse-type ground motions

This work focuses on simplified pulses simulating ground motions such as exponential, rectangular, sinusoidal and triangular waveforms. The reader can consult Ref. [13] for more information about the application of these pulses in Single-Degree-Of-Freedom systems. The examining cases could make available valued conclusions the intense earthquake response of offshore platforms. In this study, one exponential pulse with a complete cycle is examined. The pulse period, $T_p$, or the corresponding circular frequency, $\omega_p$, defines the seismic load features. Figure 1, shows loading time-history for acceleration, velocity and displacement of ground motion, for this exponential waveform.

![Figure 1. Exponential waveform](image)

For the first-half-part of this pulse, the ground acceleration, $A_g(t)$, is given by
\( A_g(t) = PGA \left( \frac{1 - \exp\left(4\pi t / T_p\right)}{1 - \exp(\pi)} \right) \) for \( 0 \leq t \leq T_p / 4 \) \\
\( A_g(t) = PGA \left( \frac{1 - \exp\left(4\pi\left(T_p / 2 - t\right) / T_p\right)}{1 - \exp(\pi)} \right) \) for \( T_p / 4 < t \leq T_p / 2 \)  

\begin{align}
A_g(t) &= |PGA| & \text{for} & \left( 0 \leq t \leq T_p / 2 \right) \\
A_g(t) &= -|PGA| & \text{for} & \left( T_p / 2 < t \leq T_p \right) 
\end{align}

whereas similar expressions can be defined for the second-half-part for this simplified exponential waveform. Additionally, rectangular waveforms are investigated here, as shown in Figure 2, which shows the corresponding ground acceleration, ground velocity and ground displacement time histories.

![Figure 2. Rectangular waveform](image)

The ground acceleration, \( A_g(t) \), for the simplified rectangular waveform of Figure 2 is given by

\[ A_g(t) = |PGA| \quad \text{for} \quad 0 \leq t \leq T_p / 2 \]

\[ A_g(t) = -|PGA| \quad \text{for} \quad T_p / 2 < t \leq T_p \]  

Furthermore, sinusoidal pulses are also investigated, where ground acceleration, \( A_g(t) \), is given by

\[ A_g(t) = PGA \sin\left( \frac{2\pi t}{T_p} \right) \]

where \( A_g(t) \) is the ground acceleration. Figure 3 depicts the corresponding sinusoidal waveforms in terms of displacement, velocity and acceleration.

![Figure 3. Sinusoidal waveform](image)
Finally, triangular waveforms are investigated here to simulate intense ground motions. Figure 4 depicts the ground kinematic parameters (displacement, velocity and acceleration) for the case of triangular waveforms.

\[
\begin{align*}
A_g(t) &= PGA \left( \frac{4t}{T_p} \right) \quad \text{for} \quad 0 \leq t \leq \frac{T_p}{4} \\
A_g(t) &= PGA \left( \frac{2(T_p - 2t)}{T_p} \right) \quad \text{for} \quad \frac{T_p}{4} < t \leq \frac{T_p}{2}
\end{align*}
\tag{4}
\]

whereas similar expressions can be defined for the second-half-part.

Notwithstanding their effortlessness, the aforementioned waveforms can efficaciously simulate plentiful real-life claims, such as the near-fault earthquake records that have been noted close to seismic faults [16-17]. For example, ground acceleration for the Coyote Lake earthquake (6 June, 1979) in comparison with the corresponding exponential waveform is shown in Figure 5.

Furthermore, adopting the sinusoidal waveform, one can describe the Lucerne Station during Landers’ Earthquake record (28 June, 1992) where Figure 6 depicts the time history of ground velocity as well as the corresponding spectral velocity.
It is obvious that the adopted simplified waveforms can sufficiently describe real earthquakes since they effectively follow the ground motions and their spectral counterparts. It is worth noticing that there are various methodologies to replicate near-fault earthquakes using particular waveforms; one can consult the pertinent references [18-20] but the proposed study does not focus on the simulation methodologies of real seismic records with pulses but it concentrates on the linear and nonlinear behaviour of offshore platforms under the action of simplified waveforms.

3. Oil and Gas Offshore Platforms - OGOPs
Numerous types of Oil and Gas Offshore Platforms (OGOPs) have been proposed in the past where the most applied type (more than 95% of total cases) is the Oil and Gas Jacket Offshore Platform (OGJOPs) [6-7]. The elementary components of an OGJOP are: foundation (piles), jacket (which corresponds to a bracing system for the piles) and deck. The overall height of an OGJOP is the water depth and the design height of sea waves (which is assumed ten to fifteen meters). The design of an OGJOP takes into account numerous loads and loading combinations such as vertical loads (self-weight, weight of production and exploration facilities), environmental loads (wind, temperature differences, waves and seismic loads) and impacts (iceberg- and ship- percussions).

In this study, two OGJOP models are constructed by the aid of Ruaumoko dynamic inelastic finite element program [21]. Ruaumoko is adopted here considering that it can successfully simulate the post-buckling behaviour of braces and the seismic inelastic pile-soil-structure interaction. Figure 7a depicts the 3-D finite element model of the examined offshore platform.

Additionally, another finite element model has been constructed to take into account the effect of soil flexibility on structural response. Thus, Figure 7b depicts this model where foundation piles have been simulated using nonlinear beam-column elements. Furthermore, Figure 7c shows the simulation of soil medium using nonlinear springs and dashpots. For more information about OGJOP modelling, the reader can consult Refs [6, 7].

4. Selected Results
This section provides selected results from the linear and nonlinear analysis of oil and gas jacket offshore platforms under the action of pulse-type ground motions.

4.1. Linear analysis
This subsection examines the linear elastic response of OGJOPs. For completeness reasons, more specifically, Table 1 provides the first twenty eigenperiods for both models of platforms.

Figure 6. Sinusoidal waveform simulation of Landers earthquake (28 June, 1992)
Figure 7. Finite element model of OGJOP, a) Fixed platform assuming undeformed soil, b) Soil-pile-structure system for deformable soil, c) Nonlinear model of the soil-pile system

Table 1. Natural frequencies and periods for the first fifteen eigenvalues

| Eigenvalue | Fixed-base assumption | Soil-pile-structure system |
|------------|------------------------|-----------------------------|
|            | Natural frequency (rad/s) | Period (s) | Natural frequency (rad/s) | Period (s) |
| 1          | 3.199                  | 1.964          | 2.675                  | 2.349      |
| 2          | 3.572                  | 1.759          | 3.154                  | 1.992      |
| 3          | 4.488                  | 1.400          | 3.666                  | 1.714      |
| 4          | 8.470                  | 0.742          | 4.217                  | 1.490      |
| 5          | 9.587                  | 0.655          | 6.397                  | 0.982      |
| 6          | 11.278                 | 0.557          | 9.111                  | 0.690      |
| 7          | 12.837                 | 0.489          | 9.475                  | 0.663      |
| 8          | 13.729                 | 0.458          | 12.020                 | 0.523      |
| 9          | 14.118                 | 0.445          | 13.407                 | 0.469      |
| 10         | 16.148                 | 0.389          | 14.771                 | 0.425      |
| 11         | 16.776                 | 0.375          | 15.431                 | 0.407      |
| 12         | 16.845                 | 0.373          | 15.943                 | 0.394      |
| 13         | 16.936                 | 0.371          | 16.002                 | 0.393      |
| 14         | 17.059                 | 0.368          | 16.530                 | 0.380      |
| 15         | 17.097                 | 0.367          | 16.474                 | 0.381      |
| 16         | 18.121                 | 0.347          | 17.238                 | 0.364      |
| 17         | 20.207                 | 0.311          | 18.617                 | 0.337      |
| 18         | 20.603                 | 0.305          | 19.252                 | 0.326      |
| 19         | 21.068                 | 0.298          | 19.340                 | 0.325      |
| 20         | 21.124                 | 0.297          | 20.050                 | 0.313      |

It is evident that the soil-pile-structure hybrid system is more flexible, in comparison with the fixed-base model where the eigenperiods of the former appear to be higher than the counterparts of the latter. The maximum horizontal top displacement for the examined OGJOP under fixed-base conditions is examined in Figures 8-11. More specifically, this OGJOP is subjected to the whole set of simplified pulses for various circular frequencies ranged from 0.6 to 100.0 rad/s, i.e., for the period of waveform ranged from 0.6 to 10.5 s.
Figure 8. Normalized maximum displacement for fixed-base OGJOP under exponential pulse

Figure 9. Normalized maximum displacement for fixed-base OGJOP under rectangular pulse

Figure 10. Normalized maximum displacement for fixed-base OGJOP under sinusoidal pulse

Figure 11. Normalized maximum displacement for fixed-base OGJOP under triangular pulse

Figure 12. Top horizontal displacement for fixed- and flexible base of OGJOP
It is obvious that these simple pulses lead to different response between themselves. For example, rectangular waveform provides with numerous peaks with identical intensity for various loading frequencies. On the other hand, sinusoidal waveforms appear to have a discrete peak value for specific loading frequency. The load frequency $\omega=10$ rad/s appear to be critical for any pulse type under consideration. Finally, Figure 12 depicts the response of OGJOP, for both rigid and flexible soil, considering load frequency $\omega=10$ rad/s and maximum peak ground acceleration, PGA, equal to 1.0g. The difference between these cases is obvious where the rectangular waveform appears to be the most intense while the exponential pulse leads to the mildest results.

4.2 Nonlinear analysis
This subsection examines the inelastic response of OGJOPs. Without loss of generality, the rectangular and triangular pulses are applied for rigid soil, considering load frequency $\omega=10$ rad/s and various values of maximum peak ground acceleration, PGA, in order to achieve incremental dynamic analysis results, in Figure 13. It is obvious that the higher the PGA the more intense the response.

![Figure 13. Top horizontal displacement VS. base shear for various PGAs](image)

**5. Conclusions**
This work examines the seismic safety of 3-D gas and oil jacket offshore platforms under the action of pulse-type earthquakes. It can be concluded that the consideration of undeformed soil strongly affects the response in comparison with the case of deformable soil. Furthermore, each type of waveform under consideration leads to quite different results even if the circular frequency and the maximum peak ground acceleration is identical in any case.
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