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A review of fixed offshore platforms under earthquake forces

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Abstract. Advances in geological studies, have identified increased seismic activity in the world's ocean once believed to be far from seismic hazards. The increase in demand of oil and other hydrocarbons leaves no option but to install a suitable offshore platform on these seismically sensitive offshore basins. Therefore, earthquake based design criteria for offshore structures are essential. The focus of the present review is on various computational techniques involved for seismic response study. The structural and load modeling approaches, the disturbed fluid-structure and soil-structure interaction as well as hydrodynamic damping due to earthquake excitation are also discussed. A brief description on the reliability-based seismic design approach is also presented.

Keywords: response spectrum; hydrodynamic damping; soil-structure interaction; reliability.

1. Introduction

With the growing demand for energy, the exploration and production of hydrocarbons is not only limited to deeper water, but also in seismically active zones of the world's ocean. In addition, advances in geological studies, have identified increased seismic activity in regions once believed to be far from seismic hazards. Therefore, earthquake response studies for an offshore structure are of immense importance. The current state-of-the-art states that offshore platforms should be able to satisfy two levels of earthquake, i.e., strength level and ductility level earthquakes (API RP2A-WSD). The strength level requirements are intended to provide a platform with sufficient strength and stiffness to ensure no significant structural damage for the level of earthquake shaking that has a reasonable likelihood of not being exceeded during the life of the structure. The ductility level requirements are intended to ensure that the platform has adequate energy absorption capacity (or reserve strength) that avoids its collapse during a rare intense earthquake. The design loads for any type of offshore structures in a seismic zone is due to seabed excitation and random sea waves. The effects of wind fluctuations are insignificant for the design of fixed offshore platforms, but for the design of compliant offshore platforms (Fig. 1), the dynamic response due to the fluctuations in wind loading/seismic loading is predominant. Generally two approaches are specified in the literature for evaluating offshore structural response to dynamic loads:

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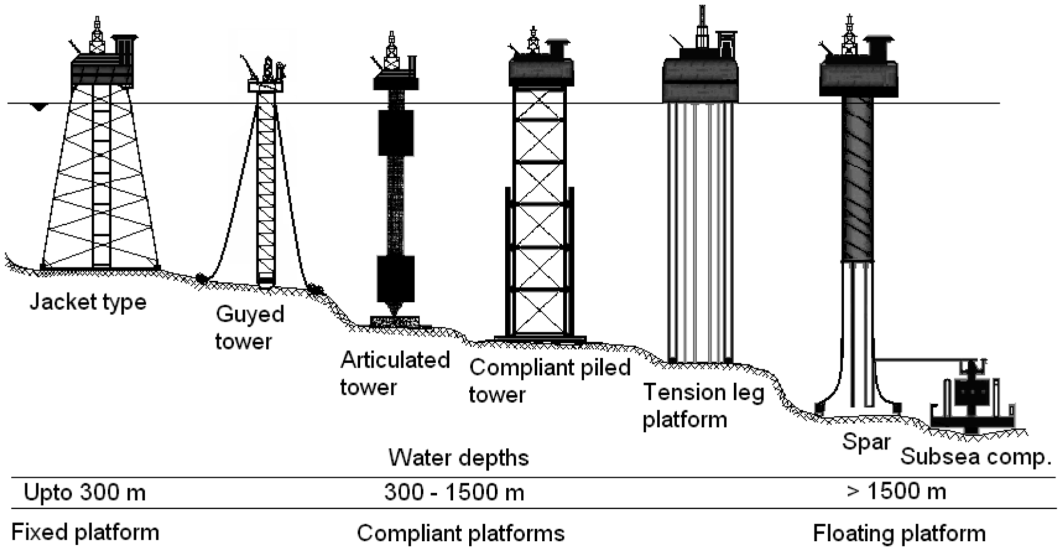

Fig. 1 Offshore structural systems

- Deterministic and
- Non-deterministic.

Adoption of a particular approach depends upon the type of loading. If the time variation of loading is fully known; the analysis for the structural response will be a deterministic analysis. On the other hand, if the time variation of loading is not completely known but can be defined in a statistical sense, i.e., random dynamic loading, the analysis for the structural response will be nondeterministic analysis. The dynamic response characteristics of offshore structures depend not only on the vibrational behavior of the structure but also on the dynamic characteristics of the soil foundation system. Upon vibration, which causes excess pore pressure and diminishing vertical effective stress, a part of the seabed may become unstable or even liquefied. Once liquefaction occurs, the soil particles are likely to be carried away as a fluid owing to the action of ocean waves. As a consequence, the seismic behavior of these structures has been investigated by many researchers. A number of issues are involved in the study of seismic analysis and behavior of offshore structures. They include: the structural and load modeling approaches, the method of analysis, effect of disturbed fluid-structure and soil-structure interaction, hydrodynamic and the structural damping. In this paper, a state-of-the-art review on seismic response and behavior of bottom fixed offshore platforms, addressing the above issues, is presented.

2. Seismic response methodologies

In general, computation of dynamic response of structures subjected to earthquake loads involves: (i) formulation of a model, (ii) mathematical formulation of the governing equations of motion, and (iii) computation of structural response. The formulation of a model requires simplification of the complete full-scale structure. This may require trials; involving verification by means of specific measurements of similar or related structures, observations of general trends in full-scale structural

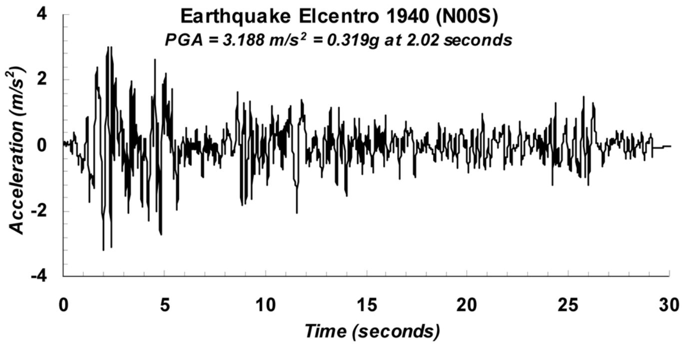

Fig. 2 Ground acceleration time history

response or of selected features of full-scale response. Model geometry and its properties may be chosen suitably to study the specific aspects of the desired response. The mathematical expressions defining the dynamic displacements are the equations of motion of the structure. The most clear-cut approach is to ascertain directly the dynamic equilibrium of all forces acting in a simple system by means of d'Alembert's principle. In a complex system, especially those involving nonlinearities due to large deformations, time-wise variation of the submergence, buoyancy, added mass, etc., direct vectorial equilibration may be difficult; therefore, work or energy formulations may be more convenient. The computation of structural response usually involves direct integration of the governing differential equations. If known time-history of the excitation is considered, time domain analysis is preferred. For linear system that can use the superposition principle, a frequency domain analysis may be performed. When there is uncertainty regarding the time-history of the excitation, stochastic methods of response estimation seems appropriate.

The seismic inputs at a location may be specified either by means of design response spectra or by time-histories with peak ground (base acceleration input Fig. 2) acceleration to characterize the maximum response.

2.1 Response spectrum approach

Response spectrum analysis is mostly suited to problems involving displacement in the elastic range while time-history analysis may be used to represent nonlinear displacement behavior. The procedure of response spectrum analysis is based on the assumption that the response in each natural mode of vibration can be computed independently of the others. The modal response is generally computed by representing structural system as single-degree-of-freedom system, because majority of them principally behaves like simple oscillators. Once the modes of vibrations are obtained, the total response (displacement, member force, base shear, bending moment etc.) for each mode can be obtained by superposition (Newmark and Hall 1982) using statistical methods such as complete quadratic combination (CQC) and square root of sum of squares (SRSS). The SRSS superposition method has been used widely for many decades; however, it performs well only for 2-dimensional and 3-D structures with no torsional rotation. On the other hand, CQC, provides accurate combination for any general configuration, therefore, its use is recommended strongly over SRSS.

2.2 Time-history approach

If time-history technique is considered, the load effect should be calculated for at least three sets of time-histories (NORSOK standard, Ed. 2, Sept. 2007) and the mean value of the maximum response may be taken as the basis for design. Each time-history must be specified by sets of 3-component accelerogram (two orthogonally horizontal oscillatory inputs and one vertical input acting simultaneously). These seismic components are assumed to be statistically independent. One of the horizontal excitations should be parallel to the main structural axis, with the major component directed to obtain the maximum value for the response quantity considered. The earthquake time-histories shall be selected in such a way that they are site-specific at the given probability of exceedance. The interaction between the soil, the structure, and the surrounding water should be taken into consideration. A significant computing effort is required for the numerical integration of the differential equation of motion using small time steps. For instance, Nair *et al.* (1980) compared the seismic response, using spectrum and time history analyses. Peak values of individual member forces were estimated. It was found that the accuracy of the SRSS (Square Root of the Sum of the Squares) method of modal combination was below satisfaction, whereas the accuracy of response spectrum technique seemed to be adequate. Bureau (1986) discusses the application of new analytical procedures that demonstrate the significance of several site-dependent factors, including nonlinear dynamic behavior of marine soils and the presence of a large body of water in the seismic design of offshore platforms. As a first step, estimation of free-field seismic parameters characterizing ground motion at mud line, nonlinear soil dynamic behavior that is significant to horizontal response, and the depth of water for vertical response. Simultaneous consideration of horizontal excitation, vertical excitation and hydrodynamic effects were further required to characterize offshore sites seismically, especially due to sensitivity of some platforms to vertical loads. These considerations were applied to the characterization of horizontal and vertical seismic design criteria for a hypothetical offshore site with a water depth of about 300 m, underlain by soft marine clays. In another study, Chen and Cao (1987) replaced the linear viscous damping term using Fourier Transform-Time Domain Iteration (MFTTDI) method. The effect of earthquake load on the nonlinear fluid drag term in the equation of motion was investigated. The proposed method showed high efficiency as well as accuracy. The method could be applied to engineering practices subjected to both earthquake and wave force. On the basis of macro element method, Kokkinowrachos and Thonas (1990) developed a numerical approach incorporating disturbed water particle behavior due to earthquake shaking around a large bottom supported offshore structure ignoring the viscosity of the surrounding water. Parameters like geometry, relative dimensions, water depth were considered. It was claimed that the developed method was computationally efficient, and can also be easily used for the analysis of the flexible structures. Nadim and Gudmestad (1990) too developed a method for the evaluation of seismic reliability of an engineering system during strong earthquake. The method was applied to evaluate the performance of offshore platforms and its component. A year later, Bai and Pedersen (1991) proposed a finite element procedure for earthquake response analysis of three-dimensional framed jacket offshore structure with geometrical and material nonlinearities. The numerical examples showed that the proposed finite element procedure was efficient as well as accurate. A numerical program (SOS_3D), capable of analyzing the inter-related aspects of fluid-structure-soil interaction of offshore structures, like jack-ups, in either two or three dimensions was developed by Bienen and Cassidy (2006). The environmental loadings such as wind, wave and current was considered. Seismic criteria and material's nonlinearity were not considered. Wave loading was modeled by the new wave theory with Pierson-Moskowitz spectrum. Current velocity was added to along with the wave kinematics. The solution algorithm was Newton-Raphson. Structural damping was set at 5% of critical for the lowest two modes. Hydrodynamic damping was calculated using the extended Morison equation. Accurate foundation modeling is a must as the footing response significantly influences the system's behavior. The program may also be used to simulate other offshore structures composed of beam-columns and shallow foundations. Another method that calculates the mean upcrossing rate of stationary stochastic processes was proposed by Naess *et al.* (2006). The model considered was the surge response of a moored deep floater in random seas. Laplace approximation was to be applied before making the method applicable for practical use.

Recent methods in which the tower was modeled as an immersed beam by combining both continuous and discrete (finite element method) approaches was presented by Wu and Chen (2007). With their proposed methodology, they examined the effect of an eccentric tip mass with rotary inertia over an offshore tower subjected to support excitation. It was stated that the time required by their method with CPU (IBM PC Pentium III) is only 2.4% of the time required by conventional FEM. Peng and Ghoneim (2009) presented a comprehensive comparison of API and ISO seismic design requirements for offshore structures. An existing platform was selected to illustrate the stress ratio comparison of the platform as per WSD and LRFD design methodologies. The selected critical API and ISO seismic requirements having significant impact on the structural design of the offshore platform included the simplified design response acceleration spectrum, the detailed probabilistic seismic hazard analysis, the uniform seismic hazard response spectrum, the tubular member strength, stability requirements and the tubular joint strength requirements.

3. Seismic and wave kinematics of offshore platforms

Offshore structures are usually subjected to more severe load conditions than those on the land. The existing know-how, research, guidelines, codes, and recommendations for offshore structure are not fully developed. There is a serious scarcity of data for earthquake-induced ocean waves. The literature available on seismic response of offshore platforms suggests that the study carried out in this area is limited. Therefore, the thrust of this section is to present an overview for an insight into the behavior of seismic response of offshore structures.

A stochastic model for horizontal ground acceleration of finite duration was presented by Penzien *et al.* (1972). The model was characterized by zero mean ergodic Gaussian process. The offshore structure was subjected to random wave and earthquake excitation. The effects of fluid-structure interaction (inertia and drag) were considered with each type of loading. The governing dynamic equation of motion as obtained with the above consideration is

$$[M^*]\{\ddot{Y}\} + [C_o]\{\dot{Y}\} + [K^*]\{Y\} = \{P^*\} \tag{1}$$

where $[M^*] = [\varphi]^T[M + \rho(K_M - 1)V][\varphi] =$ Generalized d mass matrix

$[K^*] = [\varphi]^T[K][\varphi] = [\omega^2][M^*] =$ Generalized d stiffness matrix

$[C_o] = [\varphi]^T[C][\varphi] =$ Coupled damping matrix

$$\{P^*\} = -[\varphi]^T[M + \rho(K_M - 1)V]\{\ddot{U}_g\} + \rho K_M[\varphi]^T[V]\{\ddot{V}_o\} + \{\varphi\}^T[\overline{C}]\{\dot{V}_o - \dot{U}_g\} =$$
Generalized d force vector (2)

The solution was obtained for four representative deep water towers. Based on the results, it was recommended that design wave loads should be worked out by stochastic analysis. Regarding earthquake loads, its dynamic response analysis should also be carried out either by stochastic or by response spectrum approach. It was suggested that at least two normal modes of vibration should be included in all dynamic analysis. Further, two earthquake intensities: one with lower intensity for which the tower is designed to remain elastic and another with higher intensity for which the inelastic deformations of the tower are limited to an acceptable levels should be considered. Considering response spectrum techniques, Chan (1987) analyzed the dynamic characteristics of steel template offshore platforms for seismic analysis accounting added mass of the water. Various modal summation rules were compared with different directional summation rules. On the other hand, Nadim *et al.* (1988) studied the influence of the spatial variability of earthquake motion on the response of large gravity base offshore platform incorporating stochastic kinematic interaction. The seismic environment was described as a random field varying both in space and time. Moreover, Earthquake hazard being an important factor in the design of offshore installations, Nadim, in 1991, stressed upon that the earthquake design spectra should be used at preliminary design stage, while site specific seismic criteria at detailed designing. The probabilistic and deterministic seismic hazard analyses of the region must be evaluated.

In 1993, Bea and Young studied the effect of dynamic-transient loading and the overall nonlinear behavior of the platform under extreme storms and earthquakes. The offshore structure under the study was steel template-type platform with natural frequency in the range of 1 to 5 seconds. Capacity modifiers were developed to adjust the ultimate lateral load resistance determined from static push-over analysis. These modifiers were the functions of transient loading and performance characteristics of offshore structure. The results of the study from the idealized system were correlated from time-domain nonlinear analysis. It was suggested that additional analysis of platform subjected to ultimate limit state intensity loadings are needed for further improvement of the results.

Kawano and Venkataramana (1999) performed dynamic response of large offshore structures. The heavy dead loads were reduced by buoyancy-type foundation considering soil-pile interaction. Finite element method was used to formulate the equation of motion of the superstructure, while the governing equation was obtained using substructure method. Frequency-domain random-vibration approach was considered for response analysis under the action of sea waves, currents and earthquake. The major difference in the values of bending stresses was observed in the structural responses under wave and earthquake forces owing to higher vibration modes. It was suggested that response to strong motion earthquakes are necessary, as significant nonlinear effects are anticipated.

In offshore structures, damping arises from hydrodynamic forces of the fluid surrounding the structure as well as from the structure itself. The structural damping is related to the properties of the structure, while fluid damping is the function of viscosity (skin friction) and flow separation. Hydrodynamic damping is usually higher than structural damping. This is due to the presence of waves and currents. Soil-structure interaction may also contribute towards the overall damping depending upon the soil characteristics. An appropriate value of damping is a subject of controversy in design practice. Jeng and Lin (1996) presented a finite element model for the wave-induced soil response in a porous seabed, with variable permeability and shear modulus as a function of burial depth. Three typical marine materials, course, fine sand and gravel, were considered. The finite element formulation involved a combination of semi-analytical techniques and the Galerkin method. The soil matrix was for unsaturated and hydraulically anisotropic soils, subjected to a 3-D short-

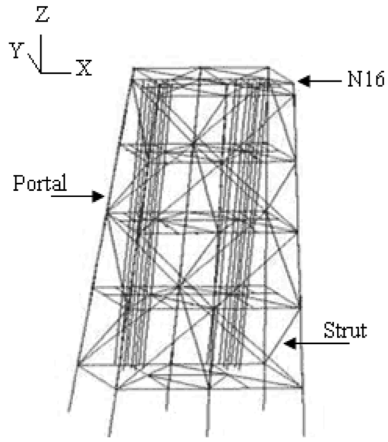

Fig. 3 Model of jacket-type platform

crested wave. The numerical results indicate that the soil permeability affects the wave induced seabed response significantly especially for graveled seabed, as does the soil shear modulus for sandy seabed. Similarly, a simple finite element model was proposed by Jenga and Lin (2000). Their method investigates the wave-induced soil response in a cross-anisotropic seabed of finite thickness with variable soil permeability and Young's modulus. Results indicated that the above parameters cannot be always ignored without substantial errors for wave-induced soil response.

Etemad *et al.* (2004) carried out their case study on jacket-type offshore platform located in Persian Gulf (Fig. 3). The structure was modeled by finite element approach, using ANSYS 5.5 software. Stokes fifth order wave theory was considered. The dynamic interaction between soil-pile was modeled by Konagai-Nogami method. The responses of the platform under earthquake and wave loads acting simultaneously were compared with the earthquake load alone. The longitudinal component of earthquake and the wave in the same direction as well as in different directions are considered in the analysis. It was stated that when both the loads are in same direction, wave may reduce the platform response; whereas, if in different directions, in some cases, there is an increase in response.

Mostafa and El Naggar (2004, 2006) investigated the response of offshore platforms supported by clusters of piles. The soil resistance to the pile movement was modeled using dynamic *p-y* curves, *q-z* curves and *t-z* curves to account for soil nonlinearity and energy dissipation through radiation damping. The wave forces on the tower members and the tower response were calculated in time domain using a finite element package (ASAS). The load transfer curves for a single pile were modified to account for the group effect. Several parameters such as the foundation flexibility, dynamic soil resistance, pile-soil-pile interaction, soil stiffness, and platform deck mass that affect the dynamic characteristics of the platform and the platform response to wave and current loading were investigated. The effect of seabed instability had resulted in the movement of soil layers that exerts lateral forces causing stresses in offshore foundation and the supported structure. The response predicted with the proposed analysis yielded excellent results. Correia *et al.* (2008) analyzed the action of earthquakes upon offshore jacket platform by means of ADINA software in time domain. Natural frequencies and nodal displacements were obtained. Critical stresses were quantified. Reactions at the base and acceleration at the top of the structure were correlated with the experimental measurements to an offshore model scaled at a ratio of 1:45. It was inferred from the results that additional care is required in the design of foundation. Moreover, the necessity of installation of seismic protection devices on the platform was recommended. Omrani *et al.* (2008) studied the nonlinear response of a typical jacket type platform, installed in the Persian Gulf, under wave and earthquake loadings. Finite element software, ANSYS, was used to model the structure. Time histories of different earthquake loadings were applied. Wave characteristics were based on local information. These loadings were applied separately and simultaneously applied in same and different directions. The results showed that the maximum response of platform under the combination of earthquake and wave loads can be higher than maximum response due to earthquake load alone.

4. Reliability-based seismic design of offshore structures

Offshore structures are complex systems. Uncertainty always exists around its surroundings. It may be due to environmental loads (wave, wind, earthquake loads, etc), structural properties, (size and shape, resistance and material parameters) and structural analysis modeling. Reliability analysis is an effective tool to treat these uncertainties. There are several performance levels of the structure, e.g., structural safety under extreme loads, normal functions and serviceability requirements under normal loads. Limit state functions can be developed either in terms of stress or deformation to evaluate the performance levels.

Popovici and Ghiocel (1986) in their paper titled "reliability of offshore platforms in seismic environments" presented a simplified procedure for reliability analysis of a steel tubular-member template type of offshore structure in a seismic sea area. Hazards investigation was based on the available statistical data of seismic, wave and wind. Peak ground acceleration and response spectrum of seismic excitation were modeled using random variables with lognormal probability distribution. The uncertainties associated with the soil-pile-structure interaction were also included in the response study. The reliability analysis was carried out for two environmental load combinations. The results indicated a rational safety level of the investigated offshore platform. The dynamic response of offshore structures to random sea waves and strong earthquake motions was investigated by Kawano *et al.* (1989). The wave-structure interaction was represented using the generalized Morison equation whereas the soil-structure interaction was idealized as a simple system of spring-dashpot elements connecting the structure with the subsoil. The dynamic equations of motion were derived by the substructure method. The response analysis was carried out using the frequency-domain random vibration approach. The response quantities were compared using the principles of first passage probabilities across specific barriers. It was shown that the effect of random sea waves enhances the reliabilities of offshore structures against seismic loading. Nadim and Gudmestad (1990) evaluated the seismic reliability of an engineering system with different failure modes. A method to evaluate the performance of an engineering system during a strong earthquake was presented. The objective of the analysis was to investigate the effect of spatial variation of earthquake loads. It was concluded that the probability of failure was of the order of magnitude smaller than the probability of failure of individual platforms. In 1993, Bea categorized the uncertainties associated with earthquake loads in two category, i.e., inherent randomness and analytical variability. These uncertainties were associated with extreme (1000 to 10,000-yr return periods) environmental loadings acting on offshore structures. Three types of offshore structures were addressed: Gravity Base Structure (GBS), Steel Pile Template and Caisson. The results indicated that it is often not possible to develop a clear-cut characterization of uncertainties. Therefore, there is a need for well-organized and definitive evaluations of uncertainties in extreme environmental loadings and load effects.

To enhance the reliability of the design of offshore structures, it is important to evaluate the exact dynamic response. If the dynamic responses can be reduced using the control methods such as passive control and active control, then the design process for offshore structure can enhance the reliability against severe load conditions. Venkataramana and Kawano (1996) performed parametric studies to assess the influence of uncertainties associated with the inertia coefficient and the drag coefficient of the Morison equation, involved in the modeling of dynamic loading processes of ocean environment. The results showed that the effects of uncertainties are closely related to the natural frequency of the structure and the predominant frequency of the wave force. These uncertainties, except the variation in the shear wave velocity in the soil, contribute significantly to the dynamic response and the first passage probability evaluation of the offshore structural systems. The reliability evaluations for a large offshore structure with buoyancy-type foundation were also investigated by Kawano and Venkataramana (1999). In doing so, large reactions at the sea bottom due to very heavy dead loads were reduced. The equation of motion for the structure was obtained by substructure method. The response analysis under the action of sea waves, currents, and earthquake loads were carried using frequency-domain random-vibration approach. The uncertainties in the values of inertia and drag coefficient, mean wave height and shear wave velocity in the soil were considered. The level crossing of extreme responses for long term behavior of the structure was examined considering first-passage probability. It was established that level crossing probability increases considerably with increasing randomness in wave force parameters. The reliability indices based upon response stresses and design stress level indicates that these indices increase with decreasing wave periods and increasing wave heights. Whereas with the inclusion of current force in addition to the wave force, the reliability index generally decreases. Finally, it was suggested to develop rational methods for the evaluation of reliability of offshore structures subjected to wave and earthquake forces as their responses have entirely different characteristics in terms of excitation duration.

Bea (1999) presented a reliability based formulation to determine earthquake LRFD parameters. A proposed conventional, steel, pile supported, tubular member offshore platform for earthquake design criteria and guidelines was considered. The formulation was illustrated with application to platforms located in five areas: offshore California, Venezuela (Rio Caribe), the East Coast of Canada, the Caspian Sea (Azeri), and the Norwegian sector of the North Sea. Site specific results were verified results from four locations, and were found to be in good agreement. The approach shall provide important informations that allows the loading and resistance factors to be varied as a function of the desired reliability for a platform; the unique aspect of its seismic environment and primary uncertainties in the earthquake loadings. Kang *et al.* (2003) performed reliability analysis of large offshore structures. To calculate the reliability index first order second moment method was considered. A new reliability analysis method suitable for offshore platforms was presented in which the first order second moment (FOSM) method was not involved to overcome the convergence problem. The systems of engineering structures can be classified into parallel systems, series systems and mixed systems. The failure probabilities of series systems and parallel systems have the following relationship

$$P_{fs} = P[E_1 \cup E_2 \cup \ldots \cup E_n] = 1 - P[\bar{E}_1 \cap \bar{E}_2 \cap \ldots \cap \bar{E}_n] \quad (3)$$

where 'P_{fs}' is failure probability of the series system, 'n' is the number of failure modes, 'E_i' denotes the event when the ith failure mode happens, $\bar{E}_i$, $P[\bullet]$ is complementary set of, expresses the calculation of probability. It was concluded that this method is highly efficient, more reliable, and simple for the reliability analysis of large and complicated structural system.

For a reliable nonlinear dynamic response Kawano *et al.* (2003) took into account the uncertain parameters associated with the material's strength and the dynamic loads such as wave and seismic forces. Incremental method in time domain was used for response analyses. The governing equation of motion with the consideration of seismic forces and restrained foundation was

$$[\tilde{M}_{aa}]\{\ddot{x}_a\} + [\tilde{C}_{aa}]\{\dot{x}_a\} + [K_{aa}]\{x_a\} = \{F_{ag}\} \quad (4)$$

$[\tilde{M}_{aa}], [\tilde{C}_{aa}]$ and $[K_{aa}]$ denote the mass matrix, damping matrix and stiffness matrix including effects on the fluid forces, respectively, and $\{x_a\}$ denotes the displacement vector. The vector $\{F_{ag}\}$ denotes the equivalent nodal force due to a seismic motion. It was shown that uncertainties in material's strength and dynamic loading play an important contribution affecting the nonlinear maximum dynamic responses. The uncertainties in the input maximum acceleration played relatively small effects on the reliability index.

Finagenov and Glagovsky (2005) carried out the seismic reliability assessment of offshore structures in two stages. In the first stage, the dynamic structural response was evaluated considering the soil-structure interaction under seismic loads. The second stage used a probabilistic model based on the reliability assumption as a probability of preserving in time the possibility to fulfill the required functions in the specified regimes and conditions of the structural operation. While, Karadeniz (2006) presented a general formulation of reliability for RC offshore structure under extreme wave loading. Initially, the strain-stress relation of the concrete in the compression zone was simply modelled as a bilinear function with ultimate values given in Eurocode 2. It was also assumed that the concrete works only in the compression zone. In the cross-section, tension stresses were carried by the reinforcement. Uncertainties in both section capacities and loading terms were considered. Reliability index were obtained. The failure function was defined on the basis of the section capacity and applied bending moments on the cross-section. Variation of the reliability index with various parameters was investigated, and most sensitive uncertainty variables were presented in the study.

Madhavan and Veena (2006) presented a methodology for computation of reliability of members of fixed offshore structures, with respect to fatigue, considering "first passage problem". The structure was modelled as a plane frame structure. Failure criteria were formulated using fracture mechanics principle. The time varying barrier was given by

$$\xi(t) = \frac{K_{IC}}{Y(a)\sqrt{\pi}}\left[a_0^{2-m/2} + \frac{2-m}{2}C\pi^{m/2}TY^m q_i f_{0i}(2\sqrt{2})^m \cdot \sigma_i^m \Gamma\left(1 + \frac{m}{2}\right)\lambda_i(\mathrm{SCF})^m\right]^{1/m-2} \quad (5)$$

Where K_{IC} is the fracture toughness of the material, $Y(a)$ function of crack size, C and m are materials constants, a_0 initial crack size, σ_i is the RMS value of stress process in the ith sea state. $\Gamma(\cdot)$ is the Gamma function, λ_i Wirsching's wide band correction factor and SCF is the stress concentration factor. It was concluded that the established fatigue reliability degradation curve can be used for planning in-service inspection of offshore platforms. Various parametric studies were also performed to have an insight into the effect of important variables on the fatigue reliability.

Hosseini *et al.* (2008) assessed the reliability of a jacket platform by considering the damage and rupture probabilities of critical members, using the results of Push-Over Analysis (POA) and nonlinear time history analysis (NLTHA). The overall reliability of the whole structure was obtained by combining the reliability of the critical members, each having its specific importance factor. Asgarian and Agheshlui (2009) evaluated parameters of probability-based method and earthquake LRFD design method for two platforms which were located in Persian Gulf. The pile-soil structure interaction was considered by using nonlinear *p-y*, *t-z* and *q-z* curve. Moreover, the buckling and post buckling behavior of the braces was considered. Sensitiveness of reliability-based method was studied. Effect of change in Structural Safety Level (SSL) and amount of uncertainties on determining earthquake induced forces were investigated. It was observed that API recommended element resistance factors were more appropriate for SSL 3. Use of X braces was recommended as mean residual strength ratio and mean ductility were out of the recommended range for the geometry of the jacket platform with chevron braces.

4. Conclusions

It is concluded that seismic considerations for offshore structures should include interaction between the structure and the surrounding water, the characteristics of the ground motion expected during the life of the platform, and the acceptable seismic risk for the type of operation intended. In order to address the issue of earthquake safety, offshore structures should be able to resist two earthquake intensities. One of moderate intensity for which these are designed to remain elastic and another of severe intensity for which the inelastic deformations of the structures are limited to acceptable limits.

The review suggests that most of the analysis is based on the hydrodynamic behavior only, and very few of the investigators have accounted the seismic criteria for offshore structures. Hydrodynamic damping due to seismic excitation is accounted by only few investigators. It is felt that more realistic models with multi degrees of freedom need to be analyzed. The maximum response can be evaluated using a random vibration analysis by means of spectral approach. Time-domain analysis is best suited to tackle the associated nonlinearities. Soil-structure interaction for offshore platforms subjected to earthquake loading should be accounted for both offshore and marine geotechnical engineering. Possibility of control devices and reliability analysis under seismic environment should be explored. Tsunami considerations may be accounted, especially for platforms in shallow water.

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