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Probabilistic seismic analysis of offshore platforms incorporating uncertainty in soil–pile–structure interactions

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ABSTRACT

In this paper a novel methodology is presented to incorporate uncertainties associated with seismic loads, characterization of structural model parameters, and description of soil properties in the probabilistic assessment of seismic-related damage of existing jacket type offshore platforms located in seismic active areas.
The main objective of this methodology is to facilitate the probabilistic analysis of soil–pile–structure interactions (SPSI) by implementing a Comprehensive Interaction Incremental Dynamic Analysis (Comprehensive Interaction IDA) method that involves the convolution of uncertainties associated with three separate elements: structure, piles and supporting soil. This quantitative seismic analysis procedure consists of: a) selecting an appropriate suite of strong ground motion records and performing a Comprehensive Interaction IDA on a nonlinear model of an existing fixed platform; b) summarizing the Comprehensive Interaction IDA results into various percentile performance bounds; and c) integrating the results with respect to hazard intensity–recurrence relations into a probabilistic seismic format. To address and propagate these uncertainties, the Latin Hypercube Sampling technique in conjunction with the Simulated Annealing optimization is applied to evaluate their effects on the structural responses with a relatively small number of simulations. The proposed methodology with the ability of incorporating uncertainties in existing platforms can be effectively used to evaluate the structural integrity in other industries.

1. Introduction

In the last two decades destructive natural catastrophes such as earthquakes and hurricanes have caused severe damage to existing infrastructure, such as buildings, bridges and offshore platforms. In many cases such damage could have been minimized or prevented if designers had better tools to evaluate structural vulnerability and functionality under different severe loading conditions. As the severity and frequency of adverse consequences of natural events are expected to increase in coming years, it is of significant importance to develop tools and techniques that can be used to better incorporate associated uncertainties involved in the assessment of vulnerability of structures subjected to extreme loading conditions. Addressing such need is a significant challenge and each type of infrastructure has its own unique issues, so a rational way to treat this problem is by investigating each type of infrastructure separately. This paper is responsive to this need and it is focused on the seismic risk assessment of offshore platforms.

Jacket type offshore platforms are among the most important structures in the exploration and production of oil and natural gas. In order to access oil and gas resources offshore, significant investment has been made in the construction of such platforms in last few decades all around the world. Since these platforms and installed equipment play a very important role in the production line of oil and gas, any damage that they may sustain during a natural catastrophe, such as an earthquake, could result in devastating physical damages as well as business interruption losses. The seismic design criteria of the American Petroleum Institute, API-RP2A incorporates both strength and ductility requirements to ensure that a structure will maintain its structural integrity under severe loading conditions. Under a Strength Level Earthquake, no significant damage should occur for events with 200-year return period. For a Ductile Level Earthquake, structural damage is acceptable provided that collapse is prevented for events with 1000 to 5000-year return period.

Since rehabilitating existing facilities to meet modern design requirements is frequently cost prohibitive from an economic and social perspective, in 1993, the American Petroleum Institute (API) [1] established an expert panel of eminent earthquake engineers to review

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the state-of-the-art practices in seismic assessment and acceptable performance for existing onshore facilities, in order to develop a consistent design and retrofit criteria for offshore structures. As a consequence, the offshore engineering community was among the first to incorporate large-scale non-linear static and dynamic analyses into the design process [2,3].

In 1988, Bea et al. developed a framework to assess and maintain older platforms. The study conducted by the petroleum industry indicated that although some of the older jacket type offshore platforms did not meet the design guidelines of that time, they may still remain fit-for-purpose [4]. In 1992, Iwan et al. [5] proposed a process for assessment of seismic safety of offshore platforms such that a consequence-dependent approach was chosen to address the structural integrity of aging platforms. In another study by Bazzurro and Cornell [6], conventional seismic hazard analysis was used in order to calculate the annual rate of exceedance of specific seismic performance levels of jacket type offshore platforms. In 1995, Cornel [7] suggested a robust method to evaluate the probability of failure of an offshore structure under extreme loads. He offered a set of recommended simplifications for reliability analysis, design criteria construction and risk management of offshore structural systems. In 2004, the International Standards Organization (ISO19901-2) [8] published worldwide offshore seismic zone maps and offered more site soil classifications, beyond those identified by the API. Furthermore, it proposed new features to assess fixed steel offshore structures subjected to seismic events and achieve reliability levels. In 2007, Ronalds et al. [9] employed another method in which the loading pattern corresponding to the return period of failure is utilized. In 2010, Asgarian and Ajamy [10] focused their study on the understanding the nonlinear dynamic behavior of a new designed jacket type offshore platform through Incremental Dynamic Analysis (IDA), and also defined limit states in seismic performances. Moreover, Asgarian and Shokrgozar in 2013 [11] evaluated the seismic performance of an existing jacket type offshore platform with float-over deck using probabilistic method and estimated the mean annual frequency and confidence levels.

Performance-Based Earthquake Engineering (PBEE) framework was first introduced by Krawinkler and Cornell [12] in 2000 which have been used in many studies in order to evaluate the seismic structural performance, taking into account both aleatory uncertainties (such as record to record variability) and the epistemic uncertainties. With regard to the treatment of uncertainty, the models that are currently in use have several short comings in addressing epistemic uncertainties that have to be remedied. Therefore, in this paper, a probabilistic methodology is proposed in which the simultaneous effects of aleatory and epistemic uncertainties are addressed to estimate the damage stage probability using a defined limit state function for jacket type offshore platforms. In order to incorporate the combined effects of such uncertainties, an efficient approach using the Latin Hypercube Sampling together with a Simulating Annealing technique is applied. The results are compared with similar cases but without epistemic uncertainty, i.e. where aleatory uncertainty associated with ground motion records are used only.

2. Treating uncertainty

2.1. A brief overview of seismic performance and reliability techniques

The essential core of the PBEE methodology developed by the Pacific Earthquake Engineering Research Center is a probabilistic framework to reliably estimate the seismic demand and capacity of structures. Because of the high degree of empiricism and uncertainty in predicting the seismic performance, a detailed nonlinear response history analysis is required to incorporate both aleatory and epistemic uncertainties in the structural model. In recent years, several approaches have been applied to evaluate the impacts of modeling uncertainties related to seismic demands. These approaches can provide the methods to investigate the effects of one or more random variables separately or simultaneously.

Porter and Kiremidjian [13] applied sensitivity analyses to evaluate the effects of uncertainties in structural modeling parameters in order to predict pre-collapsed performance. Also, the results of sensitivity analyses conducted by Aslani [[14] have shown that the uncertainty associated with system parameters could significantly affect seismic performance. Since sensitivity analyses alone are not sufficient to quantify the effects of uncertainties in comprehensive assessments of earthquake risk, specialized structural reliability methods can be applied to propagate and incorporate different categories of uncertainties. For example, Ibarra [15] evaluated the sensitivity of collapse capacity limit to uncertainty in the system parameters by using the First-Order Second-Moment (FOSM) method and verified the accuracy of the FOSM results by Monte Carlo Simulation. In another study, Lee and Mosalam [16] explored the effect of parametric uncertainties of reinforced concrete structure responses using the FOSM method. Haselton [17] also propagated modeling uncertainties using the FOSM method to investigate their effects in the collapse capacity of reinforced concert special moment frame buildings. They indicated that although the implementation of FOSM is simple, its accuracy is not acceptable for low probability of failure ($P_f < 10^{-5}$) or highly nonlinear responses.

Other approximation methods, such as the First Order Reliability Method (FORM) and the Second Order Reliability Method (SORM), might be applied in structural reliability analyses to approximate limit-state functions. If the failure surface has an almost linear behavior around a design point, the FORM usually works well. In contrast, if the failure surface is highly nonlinear, the SORM improves the FORM results using second order approximation in the failure function. The techniques require the knowledge of means and standard deviations of random variables and the definition of failure function. In small-scale structural problems, the FORM and SORM are simple with reasonable computational time and ensure very accurate results, but in large-scale and more complex structures, such as offshore platforms, the intensive computational tasks increase significantly during dynamic loading conditions. Moreover, it is required to employ the Monte Carlo Simulation (MCS) method to validate the accuracy of the aforementioned methods especially in strong nonlinear failure functions [18]. The implementation of MCS involves the knowledge of the probability distribution functions of all input random variables prior to the reliability analysis. For instance, Singhal and Kiremidjian [19] used the MCS method to develop motion–damage relationships for structural damage in reinforced concrete moment resisting frames. In another study, Porter and Kiremidjian [13] applied MCS in the development of probabilistic assembly-based-vulnerability functions that estimate statistical parameters of building repair costs as a function of ground motion intensity. Also, Shinozuka et al. [20] utilized the MCS method to estimate the damage to bridges and further consequences on the transportation network performance. In 2008, Liel and Deierlein applied the response surface method as a functional relationship between the input random variables and limit state criterion for structural response, such as collapse capacity limit. They used MCS along with response surface to propagate modeling uncertainties and fitted a response surface to sensitivity analysis results. They have shown that in very nonlinear structural responses, the effect of modeling uncertainties can be more significant [21].

To achieve a comprehensive structural assessment, the process of the MCS method is repeated hundreds or thousands of times. Since the crude MCS method is expensive to implement, more advanced sampling schemes, such as variance reduction techniques, have to be considered. One of the most appropriate methods the Latin Hypercube Sampling (LHS) is a suitable choice to reduce the number of simulations needed. This method, which was first proposed by McKay et al. [22], subdivides the theoretical probability distribution functions of input random variables into unequal probability stratifications. In 2002, Jones et al. [23] applied LHS to evaluate the effect of uncertainty in soil