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Sensitivity analysis of pile-founded fixed steel jacket platforms subjected to seismic loads

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ABSTRACT

The sensitivity of the seismic response parameters to the uncertain modeling variables of pile-founded fixed steel jacket platforms are investigated using the Tornado diagram and the first-order second-moment techniques. The effects of both aleatory and epistemic uncertainty on seismic response parameters have been investigated for an existing offshore platform. The sources of uncertainty considered in the present study are categorized into three different categories: the uncertainties associated with the soil–pile modeling parameters in clay soil, the platform jacket structure modeling parameters, and the uncertainties related to ground motion excitations. It has been found that the variability in parameters such as yield strength or pile bearing capacity has little effect on the seismic response parameters considered, whereas the global structural response is highly affected by the ground motion uncertainty. Also, some uncertainty in soil–pile property such as soil–pile friction capacity has a significant impact on the response parameters and should be carefully modeled. Based on the results, it is highlighted that which uncertain parameters should be considered carefully and which can be assumed with reasonable engineering judgment during the early structural design stage of fixed steel jacket platforms.

1. Introduction

Performance-based earthquake engineering (PBEE) requires accurate estimation of the structural seismic demands. One of the factors that decrease this accuracy is the uncertainties in seismic responses caused by uncertainties associated with the input parameters. Seismic responses of offshore platforms are affected by various uncertain input parameters. Through sensitivity analysis based on reliable data the expected ranges of structural responses can be identified.

Sources of uncertainty affecting structural performance are often characterized as either aleatoric or epistemic in nature. Aleatoric uncertainty stems from the unpredictable nature of events, whereas epistemic uncertainty is due to incomplete data, ignorance, or modeling assumptions (Padgett and DesRoches, 2007). In general structures, sources of uncertainty include those which affect both the structural capacity and demand including the seismic forces, material properties, and geometry. In fixed type offshore platforms another important source of uncertainty is the soil–pile properties. The level of nominal capacity required for a system will be increased with the higher uncertainty in either seismic demand or capacity. Reducing the number of uncertain variables leads to decreasing the required level of the nominal capacity of the structure under investigation and hence reducing the cost.

Sensitivity of the seismic demand or estimated fragility to varying parameters in a range of structural systems has been assessed in various studies. Kwon and Elnashai (2006) studied the effects of ground motion input and material variability on the vulnerability curves of a three-story RC structure using nine sets of ground motions. Wang and Foliente (2006) found that uncertainties due to ground motion and structural modeling are the major sources for increase in estimated structural demand for Seismic responses and reliability of a L-shaped wood frame building. Song and Ellingwood (1999) studied four welded special moment-resisting frames of different sizes and configurations that suffered connection damage during the earthquake and evaluated the seismic performance using both deterministic and stochastic approaches. Kim et al. (2011) studied the sensitivity of design parameters of steel buildings subjected to progressive collapse. Nielson and DesRoches (2006) performed a seismic evaluation of a typical configuration for a multi-span simply supported steel girder bridge for an approximate hazard level of 2% in 50 years. Padgett and DesRoches (2007) studied the sensitivity of a multi-span simply supported steel girder bridge. Jalayer et al. (2010) characterize the uncertainties in material properties and in construction details and propagate them to estimate the structural

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performance conditional on code-based seismic demand and capacity definitions. Rota et al. (2010) proposed a new analytical approach based on nonlinear stochastic analyses of building prototypes for the derivation of fragility curves for masonry buildings. Fragiadakis and Vamvatsikos (2010) introduced approximate methods based on the static pushover to estimate the seismic performance uncertainty of structures having non-deterministic modeling parameter. Celarec et al. (2012) investigated the sensitivity of seismic response parameters to the uncertain modeling variables of four infilled RC frames using pushover analysis. Dolsek (2012) proposed a simplified method for seismic risk assessment of buildings with consideration of aleatory and epistemic uncertainty. The method involves a non-linear static analysis of a set of structural models, which is defined by utilizing Latin hypercube sampling, and non-linear dynamic analyses of equivalent single degree-of-freedom models. Recently Celarec and Dolsek (2013) used simplified procedures for the estimation of seismic response parameters by considering the epistemic uncertainties for an older reinforced concrete frame, and for two contemporary reinforced concrete structures. The simplifications in the procedure are associated with a simplified nonlinear method and models for the assessment of the seismic performance of the structure, whereas the effects of the epistemic uncertainty are treated by using the first-order-second-moment (FOSM) method and the Latin Hypercube Sampling (LHS) technique.

Pile-founded offshore platforms are now being installed in seismically active and environmentally sensitive regions (Yasseri and Ossei, 2004). Failure of pile-founded offshore structure may affect not only the oil and gas production activity or the safety and serviceability of the platform but also it may have worse environmental impact. However, few studies have considered the impact of uncertainty inherent to offshore structures, which have the common complexity of geometric uncertainties found in common building structures in addition to the complexity of parameters uncertainties inherent in soil–pile structure interaction. Overall structural response and capacity of pile-founded offshore platform greatly depends on the member behavior in the nonlinear range of deformation and the non-linear interaction of the foundation with the soil. In order to identify the impact on seismic response of offshore platform, sensitivity analysis is required to investigate the contribution of those uncertain input parameters including those from soil–pile interaction on the platform overall seismic performance.

This study presents a seismic sensitivity analysis of a fixed type steel offshore platform. It addresses the important uncertain modeling parameters that may contribute significantly to the overall performance uncertainty of an offshore platform designed according to the provisions of the API, American Petroleum Institute Recommended Practice for Planning (2000). After that, a simple deterministic sensitivity methodology has been used to investigate the effect of each uncertain input parameter on some engineering demand parameters (EDP) such as the maximum top displacement (MTD) and the maximum inter story drift ratio (MIDR) of the jacket structure.

2. Sensitivity analysis methods applied

In the present study, two different methods have been adopted in the sensitivity analysis of the offshore platform structure under investigation using nonlinear dynamic analysis. These methods are based on the probability theories which are the Tornado Diagram Analysis (TDA) and the First-Order Second Moment (FOSM) methods. In TDA, the upper and lower bounds of a random variable are selected and the corresponding structural responses are obtained. The difference between such structural responses, referred to as swing, is considered as a measure of sensitivity. This method has been applied in the seismic sensitivity analysis of structures in many previous studies, (e.g., Porter et al., 2002; Barbato et al., 2010, and Kim et al., 2011). In the FOSM method, the mean and the standard deviation of input parameters are predetermined and those of the structural response are obtained through simple computation. Ibarra (2003) evaluated the collapse capacity uncertainty of frame structures under seismic excitation using FOSM principles verified through the Monte Carlo simulation method. Lee and Mosalam (2005) have also used FOSM to determine the response uncertainty of a reinforced-concrete (RC) shear wall structure to several modeling parameters. Haselton (2006) has studied the effects of modeling uncertainties on the collapse capacity of reinforced concrete frames designed for a high seismic region in California using the FOSM reliability approach. Also, Baker and Cornell (2003, 2008) have used the FOSM method in combination with numerical integration for the propagation of uncertainties in probabilistic seismic loss estimation.

3. Uncertain variables considered in the analysis

The sources of uncertainty considered in the present study consist of three different categories. The first is the uncertainties associated with soil–pile modeling parameters including axial pile–soil friction, the pile end bearing, the effect of time since the pile was driven, and the cyclic nature of loading during the pile driving. The second source of uncertainty is related to the platform jacket structure modeling parameters including structural mass, damping ratio, elements yield strength (F_y), Young's modulus (E), and the force–deformation relationship of element plastic hinges. The variation of plastic hinge property is obtained by scaling every force and deformation value on the force–deformation relationship by multiplying a single, random variable. The third is associated with the seismic excitation including ground motion intensity and ground motion profile. The variation of ground motion profile is considered by performing a set of structural analysis using a scaled ground motion profile and sorting the set of ground motion profile with respect to the magnitude of EDP values.

Based on the ISO Code 19902 (ISO, 2003) for Fixed Steel Offshore Structures, a reliability analysis has been carried out for pile axial capacity to assess the effect of different environmental load factors on foundation reliability. Statistical modelings for pile friction and end-bearing capacities have been assessed based on large scale tests (ISO, 2003). The axial capacity of a piled foundation in clay soils depends on the shaft friction, the end bearing, the set-up or effect of time since the pile is driven or last disturbed, and the cyclic nature of the loading. The capacity prediction equation assumed in the mentioned reliability analysis study for piles in clay soil under compression is as follows (ISO, 2003):

$$Q_d = (Q_f X_{friction} X_{delay} + Q_p X_{bearing}) X_{cyclic} \quad (1)$$

where Q_d is the pile ultimate bearing capacity, Q_f is the pile skin friction resistance; Q_p is the pile total end bearing; and $X_{friction}$, X_{delay}, $X_{bearing}$, and X_{cyclic} are the random variables of the shaft friction, the set-up or effect of time since the pile is driven or last disturbed, the end bearing, and the cyclic nature of the loading, respectively. The statistical properties of random variables of clay soil are listed in Table 1.

The statistical properties of structural modeling parameters are listed in Table 2. All variables are assumed to be uncorrelated. The uncertainty in dead loads including buoyancy in typical offshore platforms arises from factors such as rolling tolerances, fabrication aids, paint and fire protection, approximation in weight take-off, marine growth, etc. Based on the ISO (2003) the uncertainty in dead load can be modeled by a normal distribution with a mean bias of 1.0 and standard deviation of 0.06. Damping from water-interaction effects and foundation and structure related energy dissipation may be reasonably assumed to be in the range of 2–5%