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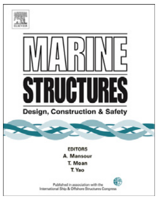

Effects of irregular nonlinear ocean waves on the dynamic performance of an example jack-up structure during an extreme event

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ABSTRACT

In this paper, the effects of the nonlinearity and irregularity of ocean waves on the nonlinear dynamic response of a jack-up structure are investigated. A finite element model of a sample jack-up platform is formulated in USFOS to include the effect of material and geometrical nonlinearity and spudcan-soil-structure nonlinear interactions. Second-order NewWave and Constrained NewWaves are developed to simulate the nonlinearity of ocean waves. The nonlinear water surface and water particle kinematics for a typical extreme wave condition are estimated and implemented in the developed model, and the results are compared in terms of deck displacements. The results obtained from the analyses indicate that the inclusion of wave nonlinearity and irregularity for the studied case produces a considerable increase in the deck displacements and in the probability of failure of the sample jack-up structure.

1. Introduction

Mobile jack-up units have been used in the offshore oil and gas industry since the 1950s. These structures contribute significantly to global offshore engineering activities, including the exploration and operation of offshore oil and gas fields and the servicing of fixed platforms. Since their initial employment, jack-ups have been used in deeper waters and harsher environments. Additionally, increasing interest has emerged in using these units for long-term assignments. Therefore, ensuring that these structures can safely sustain all applied loads and that the likelihood of their failure is acceptably small is crucial. Therefore, all uncertainties associated with the performance of these structures should be incorporated as precisely as possible. One of the main sources of uncertainties is the modelling of ocean waves. Ocean waves are irregular, nonlinear and directional, particularly those resulting from hurricanes [1].

The irregularity of waves illustrates that wave energy is distributed across a broad spectrum of the ocean environment, whereas deterministic regular wave theories such as Airy and Stokes' fifth-order (widely used in the calculation of wave loading) assume that all of the wave energy is concentrated in one or few particular frequency components. To achieve a more realistic simulation of wave loads, the simulation must incorporate all of the frequency components and, therefore, the randomness of the water surface.

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The nonlinear nature of extreme ocean waves represents the wave-wave interaction phenomenon in a wave group, producing an asymmetric water surface which causes crests to become higher and narrower whereas the troughs become wider and shallower when compared to linear waves [2,3and4]. Higher crest heights and the associated water particle kinematics because of the nonlinearity of extreme ocean waves can play an important role in the stability of structures by significantly increasing the wave loads, notably when a wave-in-deck is possible.

The directionality effect explains how extreme waves propagate in different directions with a wide range of energies and frequencies in each direction. This effect reduces the width of the crests (perpendicular to mean wave direction) and decreases the particle kinematics of the water in the mean wave direction [5].

However, because of the significant complexities, these characteristics of real ocean waves are not explicitly included in the conventional analysis procedures. Therefore, investigation of the effect of these phenomena on the performance of a jack-up unit in an extreme event at a specific field is required. Considering the limitations in the current practices, a more rigorous numerical method is required to accurately and realistically simulate extreme ocean waves. In a previous study [5], the authors broadly investigated the effects of the directionality of ocean waves. In this study, only the effects of the nonlinearity and the randomness of ocean waves are considered.

Limited research has been previously conducted on the effect of the nonlinearity and randomness of waves on the dynamic performance of offshore structures under the action of a hostile wave environment. Sharma and Dean [1] assessed the load reduction for a single pile and for a group of piles resulting from directional nonlinear (second-order) random waves. Smith et al. [2] also quantified the level of load reduction in a sample jack-up using a nonlinear directional NewWave and compared the results with linear NewWave and Stokes' fifth-order wave theories; consequently, the effects of randomness were neglected. Agarwal and Manuel [6] estimated the effect of nonlinear irregular waves on the base shear of a monopile wind turbine and showed an increase in loads compared to linear waves. Moreover, van der Meulen el al. [7] assessed the effect of nonlinear irregular waves on the fatigue load of a typical monopole offshore wind turbine, and that study noted a considerable increase in the loads. In all of the above studies, a numerical method based on a Fourier Transform technique was utilized to calculate the water surface and wave kinematics at different locations of the structures. In addition, Cassidy et al. [8,9] considered the effect of unidirectional random waves by constraining the deterministic linear NewWave [10] into a completely random background using the Constrained NewWave (CNW) method [11]; however, the nonlinearity effects were ignored.

The objective of this paper is to perform a nonlinear dynamic time history analysis for both linear and nonlinear waves and compare the results on the performance of a typical jack-up platform. NewWave and CNW are used to simulate the wave actions; thereby, the effects of randomness are emphasised in the latter. The nonlinear CNW method, which accounts for the random background of ocean waves, has not been previously used to assess the effect of nonlinearity on the performance of jack-up structures. A mathematical model for simulating nonlinear waves has been developed, and the results (water surface and wave kinematics) are then implemented in a nonlinear dynamic time history analysis of a sample jack-up platform.

2. Wave modelling

In the present study, linear and nonlinear NewWave and CNW theories are adopted in wave modelling. These wave theories are briefly described as follows.

The NewWave theory [10] is a deterministic method that accounts for the spectral composition of the sea-state. By assuming that the surface elevation can be simulated as a Gaussian random process, the expected elevation during an extreme event can be derived theoretically and the surface elevation around this extreme event is modelled by the statistically most probable shape associated with its occurrence. This is particularly useful in offshore engineering because simulating many hours of a random storm in real time is a computationally time consuming process and only a few of the wave cycles in each time series are capable of producing the extreme result [12]. The shape that is the statistically most probable and associated with the occurrence of the event is applied to model the surface elevation around this extreme event [10]. For simplicity in the numerical implementation, the NewWave shape is discretised using a finite number (N) of sinusoidal wave components.

Because a unique relationship between the wave number and the frequency is noted, the spatial dependency can also be included, which leads to the following discrete form of the linear surface elevation $\eta_w^I(X,\tau)$ for the unidirectional wave:

$$\eta_w^I(X,\tau) = \sum_{n=1}^{N} A_n \cos(k_n X - \omega_n \tau) \tag{1}$$

$$A_n = \frac{\alpha}{\sigma^2} S_{\eta\eta}(\omega_n) d\omega \tag{2}$$

where k_n and ω_n represent the wave number and angular frequency of the nth frequency component, respectively; α represents the NewWave crest elevation; $S_{\eta\eta}(\omega_n)d\omega$ represents the surface elevation spectrum, σ is the standard deviation that corresponds to that wave spectrum; $X = x - x_1$ and $\tau = t - t_1$ are the horizontal distance and time relative to the initial position