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Performance of an example jack-up platform under directional random ocean waves

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ABSTRACT

This article presents the results of nonlinear dynamic analyses that explore the effects of directionality and the random nature of ocean waves on the overall structural performance of a sample jack-up platform. A finite-element model is developed which rigorously includes the effects of the material and geometrical nonlinearities in the structure and the nonlinear soil-structure interaction. Two wave theories, NewWave and Constrained NewWave, are adopted to simulate the water surface and water particle kinematics, which are implemented in the numerical model developed. Analyses are performed for both two and three-dimensional wave models, and the results are compared in terms of the deck and spudcan foundation displacements. The results obtained from the analyses indicate that the inclusion of wave spreading can result in reductions in the deck displacements of the sample jack-up platform. The level of reduction is greater when considerable plasticity occurs in the foundation. Furthermore, the probability of failure can be significantly decreased when the wave-spreading effects are included. In addition, it is shown that the effects of wave-spreading on the response and failure of the sample jack-up is increased when wave period is decreased.

1. Introduction

Jack-up platforms, which are conventionally designed and used as mobile drilling units, have been increasingly used to operate as production platforms in deep waters. Therefore, these self-elevating units are important to the offshore community because of their broad application and unique capacity in field development and operation. The performance of these structures under the action of hostile environmental loading must be evaluated as realistically as possible to enable the owners to safely extend the applicability of jack-up units into new locations and water greater depths. This requirement necessitates progressive enhancement in the current analysis methodologies with respect to the performance assessment of jack-up structures.

Over the past decades, numerical modelling of jack-ups has been substantially developed in three major areas: structural modelling, soil-structure interaction models and ocean wave loading. In the structural-modelling area, geometrical and material nonlinearities and dynamic effects can be effectively modelled [1]. In addition, nonlinear-solutions have been considerably improved, and all of the mentioned capabilities have been incorporated into advanced commercial software (e.g., USFOS). In the geotechnical area, numerous soil–spudcan interaction models that include soil nonlinearity have been developed, some of which can straightforwardly be coupled into structural numerical models [2–5]. However, despite noticeable enhancements in ocean wave mechanics [6–11], the characteristics of real ocean waves are not explicitly represented in the current analysis procedures mainly because modelling all of the factors governing kinematics of ocean waves involve significant numerical complexities and are computationally expensive.

Extreme ocean waves propagate in different directions while carrying a wide range of energies and frequencies. In other words, offshore structures are subjected to random waves that approach simultaneously from different directions. Nevertheless, in the conventional approach recommended by the design guidelines (e.g. API [12]), wave kinematics are deterministically computed by applying regular and unidirectional (2D) wave theories. In these wave models, such as the Stokes 5th order, the effect of the random nature of ocean waves is neglected, and a kinematics reduction factor (e.g. between 0.85 and 1.00 as per API [12]) is generically used to account for the directional spreading effects (3D effects). It should be noted that for drag dominated structures such as jack-up platforms, the response is sensitive to the kinematics at the crest, as the horizontal drag forces are maximum at the crest height. However, the kinematic reduction factor, which reflects the reduced kinematics

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under the highest point of the wave crest [13], cannot represent the effect of wave spreading on a jack-up (or any other spaced offshore structure) as the variation of crest height in the perpendicular direction of the wave is neglected. Given the limitations in the current practice, a more rigorous numerical method is required to accurately and realistically simulate the random nature of extreme ocean waves and their directionality.

There is limited research on the effect of wave spreading and randomness on the dynamic performance of jack-up structures under the action of hostile wave environment. Cassidy et al. [14,15] considered the effect of randomness by constraining the deterministic linear NewWave [16] into a completely random background using the Constrained NewWave (CNW) method [17]. However, because the wave was applied on the structure as a 2D water surface elevation, the spreading effect was not studied. On-the-other-hand, Cassidy [18] addressed the effect of wave spreading on the jack-up performance using the directional NewWave; however in this case, the effect of randomness was not explicitly considered. Smith et al. [13] also quantified the level of load reduction in jack-ups using a second-order directional NewWave theory and consequently the effect of randomness again was not explicitly included. This study was extended by Smith et al. [19] and Hoyle et al. [20] by introducing a formula to calculate a kinematic reduction factor based on jack-up dimensions, wave characteristic and water depth and was intended to be applied in conjunction with a regular wave analysis. The formula was proposed by a parametric study conducted using a number of independent variables for five different rig classes. There has also been some advance studies on the directional spreading of ocean waves, such as the research carried out by Ewans [21], Forristall and Ewans [22] Gibbs and Taylor [10]. However, the application of these methods to calculate wave loading on and the response of offshore structures remains computationally expensive.

In this study, the effects of directionality and the random background of ocean waves are explicitly considered for a sample jack-up platform. The main focus is on the modelling of two and three-dimensional waves with the objective to perform a nonlinear dynamic time history analysis for both 2D waves with a kinematics reduction factor and 3D waves and then to compare the results. NewWave and CNW (i.e. NewWaves of the same height and spatial location constrained within different random seas) are used to determine the wave actions; thereby, the effects of the random background of ocean waves are emphasised. The later method, which accounts for the random background of ocean waves, has not been explicitly used to assess the effect of spreading on the performance of jack-up structures. The scope of this study is to compare the results for the 2D and 3D NewWaves and CNWs on a sample jack-up platform for a limited number of sea-states. This allows for future sensitivity studies to investigate the effects of various structural and environmental input parameters on overall structural response of jack-up platforms under 3D extreme waves.

2. Framework of Jack-up modelling

A numerical model is developed using the USFOS software [23] to investigate the effect of wave spreading and random background of waves on the dynamic performance of a jack-up unit. The sample jack-up is assumed to operate at a water depth of 106.7 m. The numerical model of this platform is illustrated in Fig. 1. The jack-up structure is symmetrical against three axes (every 120°). The hull structure is supported by three main legs that rest on the seafloor through spudcan foundations. During offshore operation, the hull structure is raised to an elevation of 131.7 m above the seafloor, as shown in Fig. 1. The jack-up legs with a centre-to-centre distance of 46 m are composed of three vertical members that are stiffened through X-braces and form a triangular truss structure which are modelled by tubular members. The total self-weight of the jack-up platform is 134.2 MN. The spudcan diameter is 17 m, the apex angle is 86°, and the amount of preload in each leg is assumed to be 80 MN (i.e., approximately twice the self-weight reaction in each leg). The first three natural periods of the structure are 8.16 s (sway in the X-direction), 8.15 s (sway in the Y-direction), and 7.14 s (rotation about the vertical axis). Different aspects of numerical modelling, including wave loading, structural and geotechnical modelling schemes, are detailed in the following sections.

2.1. Wave modelling

In the present study, the NewWave and CNW theories are adopted as deterministic and random approaches in wave modelling, respectively. These wave theories are briefly described as follows.

The NewWave theory [16] 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 theoretically determined by simulating a large crest elevation, which is particularly useful in offshore engineering. The shape that is statistically most probable and associated with the event's occurrence is applied to model the surface elevation around this extreme event [4,16]. For simplicity in the numerical implementation, the NewWave shape is discretised using a finite number (N) of sinusoidal wave components.

To include the effects of wave directionality, this method is extended by introducing another term to represent the wave direction, θ. This 3D NewWave can be discretised using a finite number ($N \times M$) of sinusoidal wave components, where N is the number of frequency components and M is the number of wave directions.

Because there is a unique relationship between the wave number and the frequency, the spatial dependency can also be included, which leads to the following discrete form of the surface elevation (η) for the directional wave [18]:

$$\eta(X,Y,\tau) = \frac{\alpha}{\sigma^2}\sum_{m=1}^{M}\sum_{n=1}^{N}[S_{\eta\eta}(\omega_n)d\omega \cdot D(\theta_m)d\theta]\cos[k_nX\cos(\theta_m) + k_nY\sin(\theta_m) - \omega_n\tau] \quad (1)$$

where k_n and ω_n represent the wave number and angular frequency of the nth frequency component, respectively, θ_m is the angle of mth wave direction, α represents the NewWave crest elevation, $S_{\eta\eta}(\omega_n)d\omega \cdot D(\theta_m)d\theta$ represents the surface elevation spectrum, σ is the standard deviation that corresponds to that wave spectrum, $X=x-x_1$, $Y=y-y_1$ and $\tau=t-t_1$ are the distance and time relative to the initial position (x_1, y_1) and initial time (t_1), respectively, and $X=0$, $Y=0$ and $\tau=0$ represent the location and time of the wave crest, respectively. Thus, the spatial field is positioned so that the crest occurs at a user-defined time and position relative to the structure.

$D(\theta)$ is a directional spreading function, which is a symmetric function around the mean wave direction $\bar{\theta}$ that defines the distribution of wave energy in a sea-state with direction and must satisfy Eq. (2).

$$\int_{\bar{\theta}-\frac{\pi}{2}}^{\bar{\theta}+\frac{\pi}{2}} D(\theta)\,d\theta = 1 \quad (2)$$

A commonly used directional spreading function in engineering applications is present in Eq. (3), where n is a positive integer and C_s is a coefficient such that Eq. (2) is satisfied. When s is zero, the energy is uniformly distributed in all directions. Observations of