SEISMIC SIMULATION OF JACK-UP FOUNDATION ON LIQUEFIABLE SOILS

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ABSTRACT

As part of J-REG JIP, a series of jack-up seismic soil-structure interaction analyses have been conducted to investigate the seismic response of offshore wind farm jack-up on liquifiable soils including the effect of pre-driving and to optimise the scope of jack-up seismic assessment for wind farms. A series of 3D finite element simulations with soil continuum have been performed in time-domain with a fully coupled, dynamic, non-linear, effective stress analysis approach using sand hypoplastic constitutive models. The paper describes the approach for simulating the jack-up seismic soil structure interaction in liquefiable sandy soils. The general responses of the jack-up under seismic loading and the key findings derived from the series of sensitivity analyses are discussed.

KEY WORDS: offshore wind farm, jack-up, spudcan, seismic analysis, liquefaction, cyclic mobility, soil-structure interaction

1. INTRODUCTION

In order to assess the potential consequences of cyclic mobility and/or liquefaction to jack-ups operating in highly seismic areas, time-domain analyses can be performed by simulating the non-linear dynamic interactions between the soil and structure using Abnormal Level Earthquake (ALE) excitations. Little information, however, is available in the public domain regarding the methods for non-linear time domain seismic analysis of jack-ups particularly involving liquefiable soils. However, the availability of computationally efficient 3D finite element software and the advancement of soil constitutive models for realistic simulations of soils subjected to cyclic loading have allowed the demonstration of the technical feasibility of seismic assessment for jack-ups.

Galanez-Alvarez et al. [1] presented a seismic assessment for a three-legged jack-up with a full 3D structural jack-up and soil continuum model. The use of such a fully integrated model is expected to give more realistic dynamic interaction responses of the jack-up as the foundation soil undergoes cyclic softening. By Erbrich et al. [2] a total stress approach with appropriate modifications to model the effect of cyclic softening was adopted in the analysis. This approach was taken by the authors [2] due to the absence of readily available effective stress models in 3D finite element commercial software. The use of the total stress analysis involved various post-processing steps and iterations to ensure the compatibility of cyclic stress-strain relationship between that for the initial condition and the computed equivalent load cycles for all soil elements. Hofstede et al. [3] discussed a simplified seismic simulation of offshore wind farm jack-up on liquefiable soils coupled with Newmark sliding model for assessing the foundation displacements.

Unlike other offshore structures, an offshore wind farm jack-up operates at a large number of sites within the wind farm in a relatively short duration at each site. For a wind farm development campaign, an offshore wind farm jack-up also can operate with a wide range of variables due to the variation in water depth, soil condition, loading condition, and elevated configuration across the wind farm area which affect the dynamic response of the jack-up system. Considering the significant number of operating conditions and the complexity of the seismic assessment, a deterministic approach to satisfy the requirement for the individual sites and elevated conditions is inevitably prohibitive. Given the operation nature of an offshore wind farm jack-up, additional pragmatic considerations should be given to jack-up seismic assessments besides satisfying the general requirements of ISO 19905-1 [4] and ISO 19901-2 [5].

In the present study, jack-up seismic soil-structure interaction analyses have been conducted to investigate the seismic response of a generic offshore wind farm jack-up on liquefiable soils, including the effect of pre-driving and to optimise the scope of jack-up seismic assessment for wind farm development. Assessment of structural stresses was not considered and is outside the scope of this study.

2. SOIL CONSTITUTIVE MODELS

In a coupled seismic soil-structure interaction simulation, strength and stiffness degradations of soils under cyclic action reversals are key characteristics that should be captured in the selected soil constitutive model. This allows a realistic simulation of seismic demand imposed by the structure on the soil and vice versa. It is widely recognised that the best approach to model cyclic mobility during seismic shaking is to use an effective stress-based soil constitutive model. Several advanced effective-stress constitutive models capable of modelling cyclic mobility and liquefaction in sands are currently available, e.g., UBCSAND [6], SANISAND [7], PM4SAND [8], PDMY02 [9] and Hypoplastic [10]. For 3D modelling, UBCSAND model is now generally available in several commercially available software. Other models are only available in 2D environment or require a user-defined subroutine for 3D implementations.

With a proper calibration against suitable soil element tests data, such models should be able to capture the accumulation of excess pore pressure, triggering of liquefaction, post-liquefaction stability and the degradation of soil strength and modulus in the course of cyclic loading. Sand hypoplastic constitutive model parameters were adopted in the present study and calibrated using the triaxial tests data on Ottawa sand reported in Ramirez et.al [11] as shown in Figure 1.

In terms of liquefaction modelling, the comparisons show that the adopted sand hypoplastic model can capture the build-up of excess pore pressures, liquefaction triggering and post-triggering strain accumulations reasonably well for cyclic loading in undrained condition. Additionally, the agreement achieved for the monotonic drained triaxial tests also suggests that the constitutive model is able to reasonably simulate the effect of spudcan pre-driving and/or still water reactions prior to seismic loading. The soil element test simulations were also extended to generic silty sand which generally exhibits suppressed dilative behaviour and faster rate of pore pressure development and cyclic softening under the same cyclic loading compared to the clean sands as depicted in Figure 2.

3. FINITE ELEMENT MODELLING

In the present study, 3D seismic soil structure interaction simulations were performed using PLAXIS 3D Dynamics [12] using a time-domain approach with a fully coupled, dynamic, non-linear, and effective stress analysis (sand hypoplastic). A generic four-legged jack-up model was provided for this study with leg spacings of 75 m x 36 m, total leg length of 100 m and total elevated weight of 27,500 tonnes. An equivalent bar stool model was set up in PLAXIS 3D while ensuring similar global responses to that of the detailed model. The spudcan was modelled as a circular flat-bottom footing and placed at the mudline assuming a full bottom contact.

A soil domain of 135 m x 155 m x 43.5 m in size was chosen to minimise the boundary effect during the earthquake excitation considering the spudcan size and legs spacing of the jack-up. A 40 m thick soil deposit overlying a base layer with a shear wave velocity of 750 m/s was considered. The soil elements were modelled to exhibit drained behaviour during pre-driving and/or still water condition, and undrained behaviour during the subsequent seismic loading. Design earthquake motions in two orthogonal horizontal and one vertical directions were applied as dynamic input at the base of the model boundary. The free-field and compliant base boundary conditions were considered along the sides and bottom boundaries, respectively. Considering that the boundary condition at the base of the model was defined using a compliant base, the input seismic motion was taken as half of the design outcrop motion. A typical Plaxis 3D model is shown in Figure 3.

The adopted sand hypoplastic model incorporates the pressure and density dependency of soil behaviour which in the present simulation are crucial in capturing the deformations due to rearrangement of grain skeletons due to pre-driving in drained conditions. In Figure 4, the mean effective stress in the soil before and after pre-driving in dense sand is plotted. After being subjected to the pre-driving pressure of approximately 760 kPa and unloading to the still water reaction, the maximum mean effective stress in the soil beneath the spudcan is approximately 420 kPa. The state of void ratio reduction and the mean effective stress considering pre-driving effect implies an approximate increase in relative density of 15% from the initial relative density of 75% in the dense sand considered. Without pre-driving the increase in relative density solely due to the still water reaction is approximated to be 10%.

4. INPUT GROUND MOTIONS

A total of seven earthquake records with various durations and tectonic types are selected for the present study considering the tectonic type, magnitude and duration. Using the seed ground motions, spectral-matched ground motions in two horizontal and one vertical directions were developed based on target response spectra at outcrop for V_s = 750 m/s. The design ground motions were compared in terms of Arias intensity level. The Arias intensity indicates a measure of earthquake intensity level or the released energy (in m/s) and is proportional to the square of the acceleration time history. As shown in Figure 5, EQ5 ground motion is found to have the largest Arias intensity compared to the other ground motions despite EQ7 ground motion duration being twice as long. Given the largest Arias intensity level, the EQ5 ground motion is expected to result in the most onerous effects on the cyclic mobility and liquefaction potential of the soil surrounding the jack-up. On the other hand, EQ1 ground motion has the lowest Arias intensity level of all the seven ground motions. In the sensitivity analyses, EQ1 (low intensity) was used for the base cases with EQ5 ground motion ("high" intensity) and EQ7 ground motion (long earthquake). The three selected ground motions time histories are plotted in Figure 6.

For the selected ground motions, a horizontal spectral acceleration $S_a(1.0)$ of 0.17g or PGA of 0.10g at outcrop was set. The acceleration was arbitrarily selected considering the excess pore pressure development at free-field. For EQ1 ground motion, all the sand profiles considered do not undergo liquefaction, i.e., excess pore pressure ratio $r_u < 1.0$, as depicted in Figure 7. Liquefaction is triggered when higher intensity motions, i.e., EQ5 and EQ7 ground motions were applied. The Fourier amplitude of principal horizontal and vertical accelerations of the three sets of ground motions were also analysed as shown in Figure 8. The Fourier amplitude of acceleration suggests that the three sets of ground motions have a distinct predominant period and frequency content in addition to varying Arias intensity level and the motion duration.

5. SEISMIC SIMULATIONS AND RESULTS DISCUSSION

A total of 17 hypothetical cases have been simulated in this study as summarised in Table 1. The various simulated cases were intended to investigate the effects of the following aspects: 1) ground motion characteristics, 2) soil conditions, 3) leg load distributions, 4) pre-driving, 5) rig orientation with respect to direction of principal horizontal motion, and 6) leg length below hull. In this paper, the discussion will be focused on the general response of the jack-up under seismic loading and the effects of ground motion characteristics and pre-driving on the jack-up responses.

5.1 Free-field vs Jack-up Spudcan Response

The comparisons of Fourier amplitude spectrum between the acceleration of starboard spudcans and the ground motion at free surface for EQ1 input motion are presented in Figure 9. The Fourier amplitude spectrum is used to compare the motions experienced by the spudcans relative to the free surface motion. It can be noticed that the amplitude of the spudcan horizontal accelerations is similar to the free surface motion except for the amplification at a period of 0.2-0.3 sec which is close to the fundamental period of the input motion. The maximum shear stresses in the soil directly beneath the spudcans are also found greater than that at the free-field. This indicates that in an uncoupled analysis taking free-field surface motions as an input motion to a structural analysis is not necessarily conservative.

In terms of spudcan vertical acceleration, the amplitude is lower than the free surface motion for low periods and the amplification occurs around the heave natural period of the jack-up at 0.6 sec. Contrary to EQ1 motion, for EQ5 the amplitude of the spudcan horizontal acceleration is generally larger than the free surface motion and becomes similar at periods larger than 1 second. On the other hand, the amplitude of the spudcan vertical acceleration is similar to that of the free surface motion except around the heave natural period of the jack-up. During the long-duration EQ7 motion, the spudcan motions both in vertical and horizontal directions are similar or larger than that at the free surface.

Table 1 Summary of simulation cases

Case No	Ground Motion	Arias Intensity	Predriving Effect	Leg Load Distribution	Soil Profile	Water Depth	Rig Heading	S_a at 1.0s
1	EQ1	Low	Yes	Uniform	Dense Sand	40m	000°	0.17g
2	EQ1	Low	No	Uniform	Dense Sand	40m	000°	0.17g
3	EQ1	Low	Yes	Non-uniform	Dense Sand	40m	000°	0.17g
4	EQ1	Low	Yes	Uniform	Dense over Medium dense Sand	40m	000°	0.17g
5	EQ1	Low	Yes	Uniform	Medium dense over Very Dense Sand	40m	000°	0.17g
6	EQ5	High	Yes	Uniform	Dense Sand	40m	000°	0.17g
7	EQ5	High	No	Uniform	Dense Sand	40m	000°	0.17g
8	EQ5	High	Yes	Uniform	Medium dense over Very dense Sand	40m	000°	0.17g
9	EQ5	High	Yes	Non-uniform	Dense Sand	40m	000°	0.17g
10	EQ1	Low	Yes	Uniform	Medium dense silty Sand	40m	000°	0.17g
11	EQ1	Low	No	Uniform	Medium dense silty Sand	40m	000°	0.17g
12	EQ5	High	Yes	Uniform	Medium dense silty Sand	40m	000°	0.17g
13	EQ1	Low	Yes	Uniform	Dense Sand	40m	060°	0.17g
14	EQ1	Low	Yes	Uniform	Dense Sand	40m	030°	0.17g
15	EQ7	High	Yes	Uniform	Dense Sand	40m	000°	0.17g
16	EQ1	Low	Yes	Uniform	Dense Sand	10m	000°	0.17g
17	EQ1	Low	Yes	Uniform	Dense Sand	40m	000°	0.34g

5.2 Spudcan and hull motions

Example time histories of the spudcan and hull motions including acceleration response spectra are presented in Figure 10 for simulation case 1. In terms of horizontal acceleration, the maximum value of the spudcan response is significantly higher than that of the hull. This behaviour is showed more clearly by the comparison of the spectral response and the Arias intensity level of the motions (Figures 10 and 12). The maximum response of the hull occurs around the jack-up sway/surge period of 4 sec. This fundamental period is relatively far from the predominant period of the soil at the spudcan level which is approximately 0.5 sec.

The maximum vertical acceleration at the spudcans and the hull are found to be similar. The Arias intensity level of the vertical motions also shows that the hull experiences somewhat larger or similar intensity of motions to that at the spudcan level. This can be attributed to the stiffer response of the structure (relative to the soil) in the vertical direction and the relatively shallow water depth (and hence the leg length below hull) modeled in the study.

5.3 Spudcan displacement

Example time histories of the spudcan vertical and lateral displacements are presented in Figure 11 for simulation case 1. The cumulative and differential (vertical) settlements of the individual spudcans during shaking are plotted together with the lateral displacements of the individual spudcans in x- and y-directions. In general, the onset of significant spudcan settlements nearly coincides with the peak acceleration of the ground motion. The spudcan cumulative settlement appears to be influenced by the duration and peak acceleration of ground motion and the sand's initial relative density which is in-line with the expectation.

For all the analysis cases and generic sandy soils considered in the present simulations, the maximum differential settlement of the spudcan ranges from approximately 0.10 to 0.25 m which seem relatively insignificant in terms of the corresponding rig inclination. However, in actual situation the potential differential settlement of the spudcan is expected to be largely dependent on the characteristics of void ratio and effective stress relationships of site-specific soils and any lateral soil variations at the spudcan location. Detailed investigation of the void ratio and effective stress characteristics or the effect lateral soil variation and the spudcan installation depth are not considered in the present simulations. For the same total elevated weight, non-uniform leg load distribution is also observed to yield more onerous response of the spudcan, particularly the differential settlement.

5.4 Effect of ground motion characteristics

The effect of ground motion characteristics on jack-up responses are summarised in Table 2 and plotted in Figures 12 and Figure 13. The Arias intensity level of the spudcan horizontal motion appears to have a positive correlation with that of the input ground motion. The correlation is, however, less obvious for the ground motion at the free surface. The spudcan vertical response and the hull motions are found to be more onerous when the soil deposit is subjected to the long duration earthquake (EQ7) with a slow rate of energy build-up. Doubling the PGA of the short duration earthquake (EQ1) seems to produce a more pronounced effect on the spudcan vertical motion rather than the horizontal one.

In terms of spudcan cumulative settlement, in general larger settlements occur as the Arias intensity level of the spudcan motion increases. However, the amount of settlement appears to have a stronger correlation with the intensity of the vertical motion of the spudcan. The spudcan cumulative settlement also increases with lower rate of shaking intensity. As observed with the case of long earthquake (EQ7 ground motion), the rate of settlement increases with more stress reversals and cyclic softening leading to a significant order of cumulative settlement. The effect of ground motion characteristics seems less prominent for the spudcan differential settlement although a long duration earthquake tends to produce larger differential settlement.

Table 2 Effect of ground motions characteristics

	EQ1	**EQ7**	**EQ5**	**EQ1**
Simulation Case No	1	15	6	17
Ground motion characteristics	Short duration, low intensity	Long duration, high intensity	Medium duration, high intensity	Short duration, high PGA
Earthquake duration (s)	27	120	63	27
S_a (1.0s) of outcrop motion (g)	0.17	0.17	0.17	0.34
Soil Profile	Dense sand	Dense sand	Dense sand	Dense sand
Initial relative density (%)	75	75	75	75
Shaking intensity rate (m/s/s)	0.025	0.012	0.016	0.100
Arias Intensity of outcrop motion (m/s)	0.13, 0.10, 0.06	0.31, 0.33, 0.10	0.40, 0.49, 0.10	0.27, 0.19, 0.11
Arias Intensity of free surface motion (m/s)	0.07, 0.09, 0.04	0.17, 0.25, 0.23	0.17, 0.21, 0.11	0.07, 0.18, 0.16
Arias Intensity of spudcan motion (m/s):				
Port forward	0.15, 0.14, 0.09	0.61, 0.57, 0.36	0.70, 0.68, 0.13	0.21, 0.21, 0.29
Port aft	0.13, 0.13, 0.09	0.63, 0.59, 0.35	0.69, 0.72, 0.14	0.21, 0.23, 0.29
Starboard aft	0.14, 0.13, 0.09	0.61, 0.60, 0.37	0.83, 0.74, 0.15	0.23, 0.22, 0.30
Starboard forward	0.16, 0.14, 0.08	0.58, 0.58, 0.35	0.74, 0.70, 0.14	0.21, 0.22, 0.30
Arias Intensity of hull motion (m/s)	0.02, 0.04, 0.10	0.23, 0.28, 0.41	0.02, 0.03, 0.18	0.02, 0.08, 0.34
Spudcan cumulative settlement (m):				
Port forward	0.25	3.94	0.44	1.08
Port aft	0.30	3.86	0.38	1.07
Starboard aft	0.25	3.71	0.38	1.00
Starboard forward	0.20	3.85	0.47	1.01
Maximum differential settlement (m):				
Between two transverse legs	0.04	0.16	0.05	0.07
Between two longitudinal legs	0.07	0.15	0.10	0.05
Between two diagonal legs	0.09	0.24	0.10	0.08

Note: The Arias intensity levels presented are in x-, y- and z- directions

5.5 Effect of pre-driving

In terms of spudcan cumulative settlement, the pre-driving is shown to somewhat reduce the settlement. However, the reduction in the spudcan cumulative settlement appears to be less significant when the higher intensity motion EQ5 is applied. It should be noted that this behaviour is observed from the homogenous dense clean sand and uniform loading considered in the simulations. In actual situation, the reduction in spudcan settlement due to pre-driving is expected to be largely dependent on various factors, e.g., characteristics of pressure-void relationship of site-specific soil, any lateral soil variation at the spudcan location and leg load distribution. In sand mixtures with a significant content of plastic fines or in sandy silts, effect of pre-driving is expected to be more significant. With higher fines content, the interfine grain contact becomes predominant and begins to more significantly contribute to the mechanical behaviour of the soil mixture. The compressibility of such soils will also be closer to the clay behaviour that is uniquely determined by the current state of stress. In view of the complexity of silty soils, advanced laboratory tests data should be leveraged to capture realistic soil response in numerical simulations. Site-specific monotonic consolidated undrained tests can be used to better estimate the undrained shear strength of soil after pre-driving.

6. SUMMARY

A series of numerical simulations of jack-up seismic soil-structure interaction analyses have been performed in this study and are focused on understanding the spudcan responses on liquefiable soils for a representative structural characteristic of a generic offshore wind farm jack-up. The study suggests that non-linear time domain seismic analysis of a jack-up particularly involving liquefiable soils is feasible with the use of state-of the-art numerical model and should be able to address the inherent uncertainty in the fully uncoupled approach. For realistic simulation of foundation soil response and its effects on the structural integrity, input parameters for the selected soil constitutive models should be derived from calibrations against both appropriate monotonic and cyclic soil element tests. Due to the complexity of seismic soil-structure interactions, use of generic correlations to derive key input soil parameters should be made with caution to avoid unrealistic and non-conservative responses of site-specific soils.

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