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NUMERICAL MODELLING OF JACK-UP RIG SPUDCAN INTERACTION WITH NORMAL FAULTS

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Abstract
The jack-up rig is the most common type of mobile offshore platform that can be deployed in active faulting zones. However, its interaction with earthquake–induced fault ruptures is poorly understood. Fault rupture–foundation interaction is of paramount importance to the overall response of the structure to faulting–induced loading and in developing deployment or platform design strategies that may mitigate risk to the platform. In this paper 3D finite-element (FE) modelling is used to explore the interaction between rupturing faults and spudcan foundations. The FE models are initially employed to explore the interaction between spudcan foundations and a rupturing normal fault, followed by a parametric study investigating the influence of the fault rupture location on the structure.

1. Introduction

Anastasopoulos et al., (2007) reveals that during a seismic event, the surface rupture of an earthquake fault may cause two types of ground movement:

- transient shaking; and
- permanent ground displacements.

As fault displacement occurs, seismic waves propagate from the fault plane over large distances. These transient, oscillating waves reach the ground surface and consequently can have a significant effect on structures placed on the seabed. On the other hand, permanent ground displacements only cause offsets at the seabed if the fault propagates all the way to the ground surface (Faccioli et al., 2008). Consequently, earthquake engineering research has focused predominantly upon seismic shaking with little attention to understanding fault-rupture effects on the overlying soil and structures situated upon it (Anastasopoulos et al., 2007).

"Fault rupture-soil-foundation-structure interaction" (FR-SFSI) refers to the interaction of a rupturing fault propagating towards the ground surface, whilst deforming the soil and interacting with foundation-structure systems. Bray et al. (1994) and Anastasopoulos et al. (2008) demonstrate that when no structure is present (in the free-field), the propagation path and the surface scarp magnitude depend on three factors:

- the overlying soil (stiffness and strength);
- the magnitude of fault offset at bedrock; and
- the type of fault (dip-slip or strike-slip).

In the presence of a structure, the extent of soil deformation can vary and in some cases the fault can be diverted when the structure is heavily loaded or in the case of a continuous and rigid foundation system (Anastasopoulos et al., 2008).

Onshore investigations highlighted the considerable damage that can occur when faults interact with foundations (Ahmed and Bransby, 2009). A rupture can be diverted around a structure, provided that the bearing stresses are large enough, yet light structures will slip on their foundations, or the foundations may indeed rupture as the fault ruptures in the soil (Ahmed and Bransby, 2009; Berill, 1983).

The significant effect of dip-slip faults interacting with engineering structures was highlighted after the 1999 earthquakes in Turkey and Taiwan where normal and reverse faults ruptured at the surface (Ahmed and Bransby, 2009). Numerous structures of varying types experienced severe damage or even collapsed as a result of tectonic displacements ranging from 2m to 8m (Faccioli et al., 2008). A jack-up rig being subjected to such tectonic displacements, coupled with the risk of operating in an offshore environment, could prove catastrophic for the platform and for personnel on-board. Therefore, there is a need to consider the problem of FR-SFSI for offshore structures, to allow risk mitigation and assure platform integrity.

2. Methodology

Jack-up rigs are widespread, mobile offshore drilling and service platforms, for use in shallow water environments. They typically consist of a triangular, buoyant hull with three independent legs situated on spudcan foundations. Spudcans are roughly circular in plan with a conical base, often with a tip known as a spigot which helps with initial seabed penetration and lateral stability whilst in operation.

Such rigs are specifically designed to be mobile, operating at many sites throughout their service life; they are not purpose-built for a specific environment. Before installation, a site-specific assessment is conducted to ensure suitability of the rig for the specific environment. Under the guidelines of the Society of Naval Architects and Marine Engineers (SNAME) (2008), for the evaluation and prevention of fault risks, it is recommended to conduct a "detailed geotechnical and geophysical investigation, revealing near surface soil stratigraphy". Within these guidelines, the suggested depth of such a survey should be equal to the greater of 30m, or the anticipated footing penetration plus 1.5 to 2 times the footing diameter. The International Organisation for Standardisation (ISO) (2004) suggests avoidance, but when this is not possible, fault magnitude and time scales of expected movement should be determined.

Such code recommendations are useful, but suffer from the following issues:

- They focus on revealing pre-existing faults, specifically those located near the ground surface. Some ruptures in the free-field are not continuous and do not precisely follow the surface outcrop of pre-existing faults (Ambraseys and Jackson, 1984).
- Secondary fault ruptures may ocurr at some distance from the main trace (as far as 12km) and can displace as much as 20% of the main fault displacement (Bonilla, 1970).
- Subtle faults may also appear as changes in the waveform causing misinterpretation by geophysicists (Neves et al., 2004).

The emergence of new faults is not addressed within such industry codes and it is not known how jack-up rigs will perform when subjected to such tectonic loading, whether it be from fault reactivation or from newly emerging faults. The present research is important in exploring the overall performance of the foundation-structure system, as avoidance may be unecessary or over-conservative.

The soil-foundation interaction plays a vital role in system response. From an array of numerical and experiemental testing, it is well documented that jack-up spudcan stiffness influences the structural stiffness and thus overall system response (Bienen, 2007; Cassidy et al., 2004; Howarth et al., 2004). It is highlighted by Bienen (2007) that the capacity of the spudcans and mode of failure depend on the path of combined loads transferred to the foundation. It is therefore critical that the numerical procedure incorporates this soil-foundation-structural system, enabling the prediction of the global structural response.

The spudcan model, equivalent structural members and fault loading model are incorporated into the FE methodology for the analysis of the jack-up response in three-dimensional space. The problem is shown schematically in Figure 1. The overall objective is to employ non-linear finite-element (FE) modelling to:

- conduct a free-field analysis to determine the location of the outcropping fault, in the absence of a structure;
- investigate normal fault rupture propagation and its interaction with spudcan foundations; and
- determine the influence of spudcan response on the overall performance of the jack-up rig.

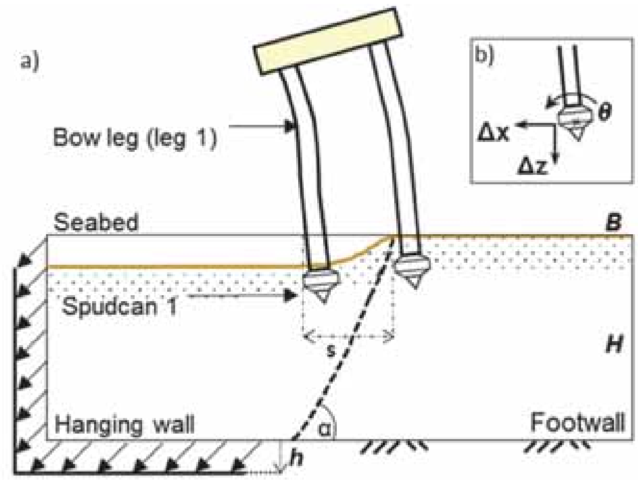

Figure 1: 2D Schematic of the problem definition: (a) fault rupture propagating and interacting with the spudcan foundations (b) spudcan displacements and rotation (x marking the spudcan reference point: SRP)

A three-legged jack-up rig is embedded to its operational depth beneath the seabed, into a soil layer of thickness *H*. Future analyses will incorporate installation disturbance of the soil immediately around the footing, however within this preliminary stage it is not considered. The boundary conditions of the sides are fixed, whilst the top is free to move in all directions. The boundary conditions of the left side and base boundary of the hanging wall block are adjusted downwards and to the left with each iterative step, simulating normal fault propagation. The fault ruptures and outcrops at the seabed where it may interact with the foundations of the rig. The distance between the left edge of spudcan 1 and fault rupture is referred to as s, α = fault dip, h = fault throw (vertical displacement).

The modelling methodology involved four stages. According to previous research on the subject (e.g., Bray et al. 1994), soil conditions play a key role in fault rupture propagation. Therefore, in stage one loose and dense sands were modelled to investigate the influence of the overlying material on fault propagation and rupture in the free-field. In the second stage, a single-footing model was developed to investigate the interaction between the spudcan and the rupturing fault. Taking advantage of problem symmetry, half of a spudcan is considered in this model, along with a leg section (Figure 2).

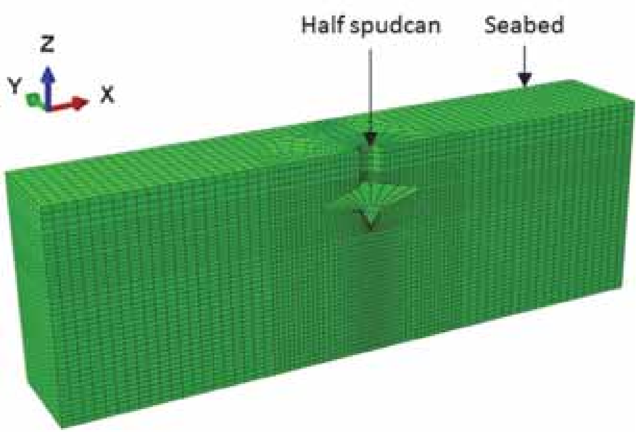

Figure 2: FE model of first stage analyses: half a spudcan foundation is modelled

An equivalent vertical static load is considered, corresponding to one third of a full rig. The properties of the investigated idealised sands are summarised in Table 1. A single Poisson's ratio was used throughout the homogenous block and stiffness for each layer was assigned manually.

In the third stage, the entire jack-up rig was modelled, including the superstructure (rig), the three spudcans and the soil. This more elaborate model (Figure 3), which is still under development, was used to conduct a parametric study, whereby the location of the fault rupture varies. The proximity of the rupture location to the structure, defined as *s*, is measured from the left edge of the bow foundation (spudcan 1) of the rig, as shown in Figure 1.

Table 1: Key properties of soil and structure

Sand	**Stage 1 & 2**		**Stage 3**
	Loose	**Dense**	
Relative density %	45	80	84
φ_p (°)	30	45	45.8
φ_{res} (°)	25	30	30
Ψ (°)	5	15	15
v	0.3	0.3	0.3
Structure			
Hull volume (m^3)	2160		
Leg length (m)	89		
Spudcan diameter (m)	10		
Rig weight (MN)	150		

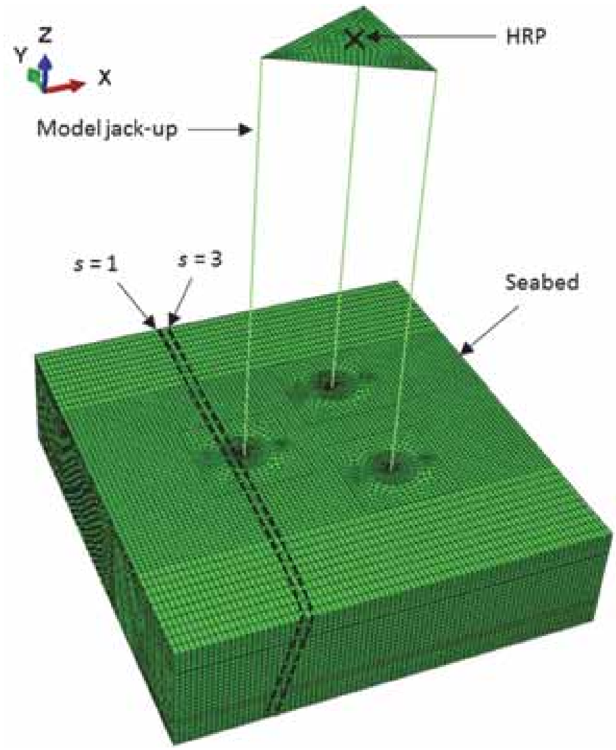

Figure 3: FE model of second stage of analyses: superstructure model and hull reference point (HRP) with schematic of parametric faulting analyses (s = 1 and 3) to be conducted

As shown schematically in Figure 3, the parametric study aims at assessing the role of FR-SFSI and determines the effect of fault rupture location relative to this spudcan. This stage also assesses the influence of the behaviour of the spudcan on the global structural response. Despite its completeness, the full model is quite extensive and the computing time required can be very substantial.

In the fourth stage, a simplified model was developed, aiming to reduce the computing time. The simplified model, which will be presented in detail in a future publication, incorporates the methodology proposed in Anastasopoulos & Kontoroupi (2014), according to which the spudcans can be replaced with non-linear springs to reduce computational expense.

3. Finite-Element Modelling Procedure

Previous studies have shown that the (FE) method can simulate fault rupture propagation through soil with reasonable accuracy (e.g., Bray et al., 1994; Anastasopoulos et al., 2007), as well as its interaction with surface and embedded foundations (Anastasopoulos et al., 2009; Loli et al., 2012).

The soil is modelled with non-linear 8-noded brick-type elements, the response of which is governed by the elasto-plastic constitutive model described by Anastasopoulos et al. (2007). It defines failure using the Mohr–Coulomb failure criterion and employs isotropic strain softening to degrade the friction (φ) and dilation (ψ) angles linearly with plastic strain, reproducing the faulting associated mechanisms of shear localisation and propagation of rupture planes. The employed constitutive model has been thoroughly validated against experimental centrifuge model tests conducted at the University of Dundee (Anastasopoulos et al., 2007, Bransby et al., 2008; Anastasopoulos et al., 2009, Loli et al., 2012).

A small-deformation analysis methodology is employed. As the priority is on the foundation system and less so on the structure, second-order effects (P-Δ effects) are not accounted for in these analyses and large-deformation analyses are not required as the fault propagates through small interative steps. No time effect is considered. Initially in stage 1, the fault propagation and rupture is modelled in the free-field (i.e. ignoring the presence of the structure). This causes downward displacement of the hanging wall (left side of the model as shown in Figure 1), of vertical magnitude h. In the second stage, the interaction between the rupturing fault and the foundation is analysed.

The mesh is refined at the area immediately around the footings and to a depth of 18m in the expected area of fault propagation. A coarser mesh extends further away from the footings. The soil is divided into layers allowing soil stiffness to increase with depth. The soil is a uniform sand deposit of thickness H = 22.5 m, with the key properties in Table 1. Following the recommendation of Bray (1990), the length to height ratio of the model is $B = 4H$ to minimise undesired boundary effects. In the first stage, sensitivity analyses were conducted confirming the validity of the above recommendation.

For the third stage of analyses, the structure is based upon an average steel three-legged jack-up rig, the properties of which are summarised in Table 1. The hull is modelled with 3D shell elements, whilst the legs are represented using equivalent beam elemements (as allowed for in SNAME (2008), when modelling structural members). This was deemed most appropriate as the focus of the project was to determine the influence of foundation behaviour on the overall rig response, as opposed to a detailed analysis assessing individual leg stresses. The spudcans are built with shell elements and are embedded to an operating depth, $0.5D$, beneath the seabed. The spudcan-soil interface is modelled with special contact elements, which are infinitely stiff in compression, but offer no resistance in tension, following Coulomb's friction law. This enables realistic modelling of detachment and slippage of the foundation from the soil.

4. Results and Discussion

The 3D models are used to predict the location of fault rupture outcropping in the free-field and the performance of the structure. Of special interest is the behaviour of the spudcans subjected to the tectonic deformation. The results focus on the vertical and horizontal displacements and the rotation of the spudcan with respect to the y-axis: Δz, Δx and θ, respectively. The results are shown for the SRP and the HRP (see Figure 1b and **Error! Reference source not found.**, respectively).

4.1 Stage 1 and 2- free-field and single-footing model

Figure 4 presents the deformed system with superimposed plastic strain contours for the free-field and the single-spudcan models. The results are plotted for fault throw (vertical offset) h = 2m. In all cases examined, the fault rupture starts propagating from the same location at bedrock, enabling the influence of the overlying soil to be investigated and to compare its effect on spudcan displacements and rotations.

Qualitatively comparing free-field fault rupture propagation through loose and dense sand (Figures 4a and 4b), it may be observed that the shear zone is steeper and more localised in dense sand. The dense sand fault dip averages at 73°, whereas the loose sand dips at an average of 60°. Due to the difference in the steepness of the propagation path, the rupture location varies by about 6m at seabed. These findings are in accord with previous work on the subject (e.g., Bray et al., 1994; Anastasopoulos et al., 2007).

In the case of the footing being situated in loose sand (Figure 4c), the fault propagates and directly intercepts the spudcan before continuing to rupture all the way to the surface. The presence of the footing significantly diverts the propagation path around the right side of the spudcan. When comparing to the free-field case, the rupture location has shifted towards the footwall (right) and differs laterally by 7m. The spudcan has shifted downwards and to the left, rotating anticlockwise by 5.5°, displacing laterally towards the fault by 0.94m and vertically downwards by 2.09m. There is significant plastic strain on either side of the footing and secondary rupture has developed on the left edge of the footing. The response is qualitatively similar to that of caisson foundations (Loli et al., 2012).

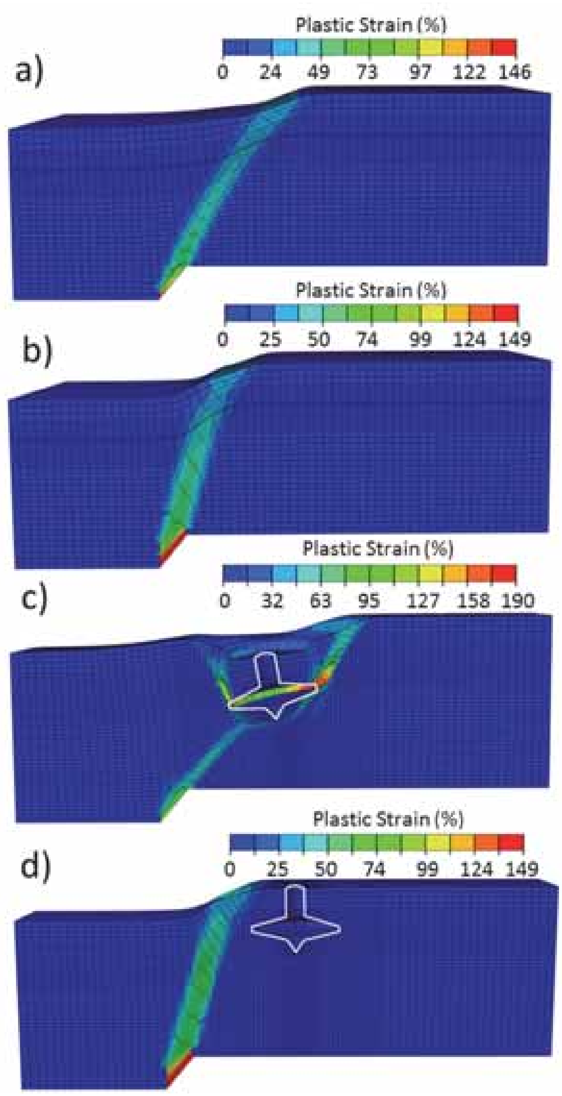

Figure 4: First stage analysis results. Deformed mesh with superimposed plastic strain contours for: (a) free-field fault rupture propagation through loose sand; (b) free-field, dense sand; (c) interaction with a spudcan in loose sand; and (d) interaction with spudcan in dense sand

In the dense sand case (Figure 4d), the fault did not intercept the spudcan directly. However, upon inspection of the magnitude of plastic shear strain, the shape of the shear zone has been slightly modified at the point just before rupture and the differential movement along the slip plane is more pronounced towards the ground surface than in the free-field. The footing rotated anticlockwise by 0.2°, displaced laterally towards the fault by 0.03m and downwards vertically by 0.1m. The outcropping location of the rupture is not altered and minimal plastic strain occurs around the footing in relation to the loose sand.

4.2 Stage 3- superstructure model

A preliminary parametric investigation has been conducted whereby the fault (h = 0.9m) propagates and ruptures at two locations (s = 1m and 3m) in dense sand (choice of soil state based upon planned centrifuge testing and the potential for dilation effecting fault propagation near the surface). This means that in the free-field, the fault rupture would outcrop at a distance of 1m and 3m from the left edge of spudcan 1. In these cases, the fault propagation path at s = 3m takes a more direct path towards the centre of the spudcan, whereas at s = 1m it clips the edge of the spudcan (inferred from Figure 5). Both cases caused displacements and rotations at all spudcans, however a more significant impact is seen at spudcan 1, therefore these results will focus upon this footing and the hull.

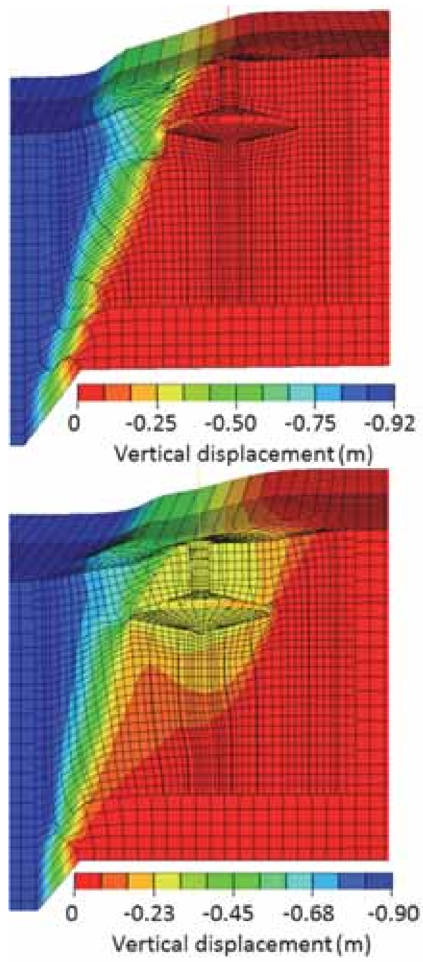

Figure 5: Third stage analyses. Deformed shape with vertical displacement contours (Δz) for interaction of the fault rupture with spudcan 1 at distance: (a) s = 1m and (b) s = 3m (deformation scale factor = 4)

4.2.1 Spudcan response

The displacements and rotations of spudcan 1 are shown in Figures 5 and 6. A notable difference between s = 1m and 3m can be observed. As shown in Figure 5, the closer the fault rupture location, the more vertical spudcan displacement occurs (a response observed comparing Figure 4c and 4d). For s = 1m, the spudcan experiences a downwards vertical displacement of 0.07m, whereas at s = 3m the downwards vertical displacement is more significant reaching 0.25m. For s = 1m, the left lateral displacement and anticlockwise rotation reach 0.03m and 0.09°, respectively. For s = 3m, they increase substantially to 0.16m and 0.36° respectively in the same direction.

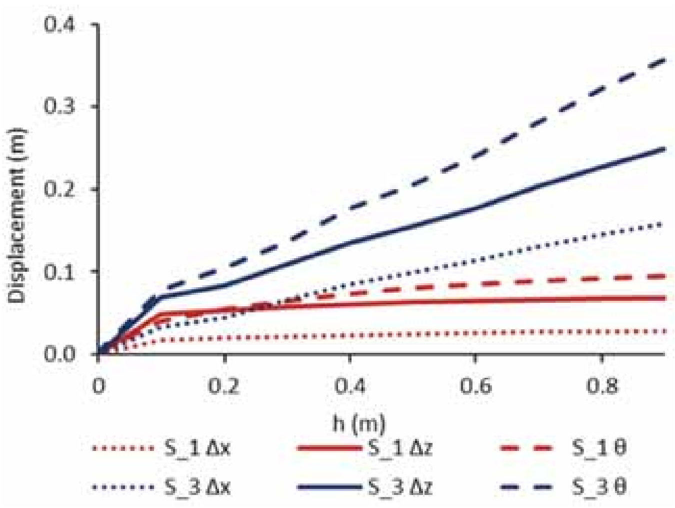

Figure 6: Displacements (Δx, Δz) and rotations (θ) at spudcan 1 for *s* = 1m and 3m

The cases investigated in the preliminary stages of this work are not considered 'worst-case' scenarios. The fault throw (vertical bedrock offset) in these cases was 0.9m. Relatively, this is not large when comparing against the faults produced during the 1999 Kocaeli, Turkey (Mw = 7.4) earthquake which had throws averaging 2.4m (Bray 2001). Consequently, a larger fault with a more significant throw could result in more extensive displacements and rotations at the footing. This could be much more detrimental to the spudcan foundation and the global jack-up rig system. Such a scenario in loose sand could cause increased dislocations and perhaps cause the two trailing footings to behave similarly to the pile group effect whereby 'shadowing' causes the loss of soil resistance at the trailing piles, as observed by (Brown et al., 1988).

Additionally, the location of the fault rupture relative to the spudcan for the studied cases of s= 1m and 3m are also not 'worst-case' scenarios. With direct fault-spudcan interception, one could predict that the footing and therefore the global structure would undergo increased displacements and rotations. Further testing will be conducted to investigate these factors further.

4.2.2 Structural response

Using results from the case of *s* = 3m, the influence of the spudcan behaviour on the structural response is analysed and presented in Figures 7 and 8. It is seen in Figure 7 that the magnitude of displacements and rotations at the hull is higher than at the footing. The hull displaces more than spudcan 1 in all directions; vertically, the hull undergoes an additional 0.002m of downwards displacement, left laterally it displaces a further 0.59m and rotates more in an anticlockwise manner by 0.1°.

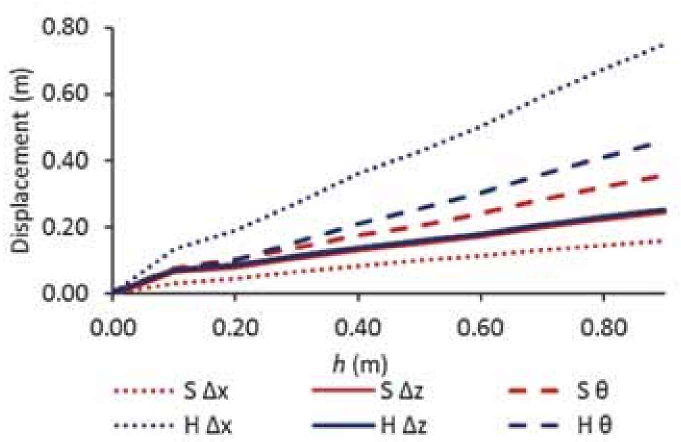

Figure 7: Spudcan 1 response (S Δ*x*, S Δ*z*) and S θ) and hull response (H Δ*x*, H Δ*z*) and H θ)

The higher magnitude of displacements and rotations experienced at the hull may increase the accident risk of the rig, particularly if a more significant fault with a larger throw ruptured near to the foundations.

The leg bending moments (shown in Figure 8) express the flexural distortion of the structure due to the imposed tectonic loading. The top of leg 1 is being compressed with a bending moment of -0.2MNm, whereas at the bottom of the leg it experiences tension with a bending moment of 0.04MNm. The bending moments in legs 2 and 3 oppose that of leg 1, at the top they average 0.08MNm and -0.09MNm at the bottom.

The occurrence of hull displacements and rotations and leg bending moments show that the FE methodology is capturing an interaction between the soil, foundation and structure. These factors, which affect overall (global) structural stiffness, alongside other aspects that govern the structural system which have not been included within this paper (e.g. mass redistribution between the footings) will be validated in the future against centrifuge testing.

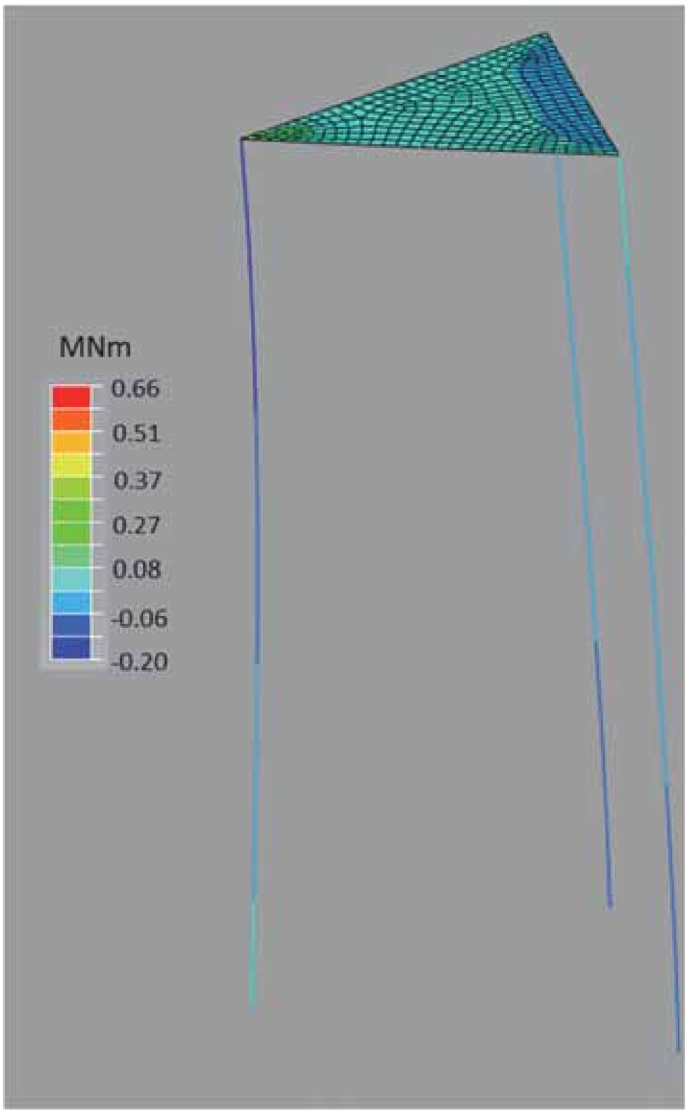

Figure 8: Leg bending moments (deformation scale factor = 50)

5. Conclusions and Future Steps

This paper uses FE modelling to conduct a preliminary study on the behaviour of jack up rigs subjected to normal faulting. Free-field and single-footing models are developed to investigate the influence of soil conditions and the interaction of the fault rupture with the spudcan foundation. In the third stage, a model incorporating the superstructure of the rig is employed to conduct a small preliminary parametric study to explore the effect of fault rupture location on the response of the rig. The key findings of the study can be summarised as follows:

1. The soil density significantly affects the fault propagation path and the location of fault outcropping at seabed;
2. Depending on the relative location, the spudcan may substantially divert the fault rupture. Still though its displacement and rotation can be substantial;
3. Reduction of the distance of the fault rupture to the spudcan leads to a pronounced increase of displacements and rotations which may increase the accident risk for the rig and personnel on-board.

The numerical methodology is to undergo continual development and will be validated against experiments conducted on the geotechnical beam centrifuge. More detailed parametric analyses will be conducted with fault ruptures outcropping at various locations (such as direct interception or rupture between the footings). Variables such as fault type, dip angle, throw and soil properties will also be varied.

6. Acknowledgements

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7. References

Abaqus. (2004). *Abaqus V6.14 User's Guide*. Rhode Island, USA: Dassault Systèmes.

Ahmed W. and Bransby MF. (2009) Interaction of Shallow Foundations with Reverse Faults. *Journal of Geotechnical and Geoenvironmental Engineering* 135(7): 914–924.

Ambraseys N and Jackson J. (1984). Seismic movements. In: Attewell PB, Taylor RK (eds.). *Ground Movements and their Effects on Structures*. Surrey: Surrey University Press. 353–380.

Anastasopoulos I, Gazetas G, Bransby MF, Davies MCR and El Nahas A. (2007). Fault Rupture Propagation through Sand: Finite Element Analysis and Validation through Centrifuge Experiments. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* 133(8): 943–958.

Anastasopoulos I, Callerio A, Bransby MF, Davies MCR, El Nahas A, Faccioli E, Gazetas G, Masella A, Paolucci R, Pecker A and Rossignol E. (2008). Numerical analyses of fault–foundation interaction. *Bulletin of Earthquake Engineering* 6(4): 645–675.

Anastasopoulos I, Gazetas G, Bransby MF, Davies MCR and El Nahas A. (2009). Normal Fault Rupture Interaction with Strip Foundations. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* 135(3) 359–370.

Anastasopoulos I and Kontoroupi Th. (2014). SDOF System Rocking on Inelastic Soil: Development of Simplified Non-linear Analysis Method. *Soil Dynamics and Earthquake Engineering* 56: 28–43.

Berill JB. (1983). Two-dimensional analysis of the effect of fault rupture on buildings with shallow foundations. *Soil Dynamics and Earthquake Engineering* 2(3) 156–160.

Bienen B. (2007). Three-Dimensional Physical and Numerical Modelling of Jack-Up Structures on Sand. PhD Thesis, University of Western Australia.

Bonilla MG. (1970). Surface faulting and related effects. In: Weigel RL (eds.) *Earthquake engineering, New Jersey*: Prentice Hall co, 47–74.

Bransby MF, Davies MCR, El Nahas A and Nagaoka S. (2008). Centrifuge modelling of normal fault-foundation interaction. *Bulletin of Earthquake Engineering* 6(4): 585–605.

Bray JD. (1990). The effects of tectonic movements on stresses and deformations in earth embankments. PhD Thesis, University of California.

Bray JD, Seed RB, Cluff LS and Seed HB. (1994). Earthquake Fault Rupture Propagation through Soil. *Journal of Geotechnical Engineering* 120(3): 543–561.

Bray JD. (2001). Developing Mitigation Measures for the Hazards Associated with Earthquake Surface Fault Rupture. *A Workshop on Seismic Fault-Induced Failures– Possible Remedies for Damage to Urban Facilities, University of Tokyo, Japan*, 55–79.

Brown DA, Morrison C and Reese LC. (1988) Lateral Load Behavior of Pile Group in Sand. *Journal of Geotechnical Engineering* 114(11): 1261–1267.

Cassidy MJ, Martin CM and Houlsby GT. (2004). Development and application of force resultant models describing jack-up foundation behaviour. *Marine Structures* 17(3–4): 165–193.

Howarth M, Dier A, Jones W and Hunt RJ. (2004). Jack-up response to wave-in-deck loads during extreme storms. *Marine Structures* 17(3-4): 275–290.

Faccioli E, Anastasopoulos I and Gazetas G. (2008). Fault rupture–foundation interaction: selected case histories. *Bulletin of Earthquake Engineering* 6(4): 557–583.

International Organization for Standardization (ISO). (2004). Petroleum and natural gas industries – Specific requirements for offshore structures – Part 2: Seismic design procedures and criteria 19901-2:2004, Brussels, 17pp.

Loli M, Bransby MF, Anastasopoulos I and Gazetas G. (2012). Interaction of Caisson Foundations with a Seismically Rupturing Normal Fault: Centrifuge Testing versus Numerical Simulation. *Geotechnique* 62(1): 29–43.

Nagaoka S. (2012). The Interaction of Earthquake Faults with Foundations and Pipelines. PhD Thesis, University of Dundee.

Neves FA, Zahrani MS and Bremkamp SW. (2004). Detection of potential fractures and small faults using seismic attributes. *The Leading Edge-Society of Exploration Geophysicists* 23(9): 903–906.

Society of Naval Architects and Marine Engineers (SNAME). (2008). Guidelines for site specific assessment of mobile jack-up units. Technical and Research Bulletin 5-5A, New Jersey, 23pp.

Spidsøe N, and Karunakaran D. (1995). Non-linear Dynamic Behaviour of Jack-up Platforms. *Marine Structures* 9(1): 71–100.

Notations

- Δx: displacement along x-axis
- Δz: displacement along z-axis
- θ: rotation about y-axis
- φ_p: peak friction angle
- φ_{res}: residual friction angle
- Ψ: dilation angle
- v: poisson's ratio
- B: soil breadth
- H: soil thickness
- h: fault throw
- s: distance between rupture location and left side of spudcan 1