AN IMPROVED ENERGY APPROACH FOR JACKUP TOUCHDOWN ASSESSMENT

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ABSTRACT

Allowable sea states for moving a Jackup on location have traditionally been determined using energy based approaches. At the design stage, assumptions such as a rigid seabed and pure roll or pitch motion, allow designers to set generic sea state limits, which have proven successful and have safely guided operations for many years. When site-specific information such as wave conditions, water depth and soil information are able to be taken into account these generic limits can be reassessed.

Recently, some efforts have been made to apply a more complex, fully coupled approach to assess the touchdown process. This approach produces time-domain simulations of the touchdown event. However, due to the complexities of the method, simplifications are still generally required and the random nature of the touchdown problem itself adds statistical uncertainty in extracting operation limits from the simulations. While traditionally less complex, the decoupled, deterministic form of the energy approach provides direct, repeatable, generation of sea state limits. With this in mind the energy method is further investigated in order to identify where improvements can be made to incorporate more of the important interactions while maintaining the same high level of reliability and repeatability of a deterministic approach to provide greater confidence to operators.

The improved energy approach presented in this paper builds on the solid base of energy based touchdown methods, adding appropriate soil-spudcan interaction and incorporating motion analysis, including heave motion in addition to pitch or roll. These changes are made possible now while maintaining the controlled form of the energy method and utilizing detailed leg and leg-hull modelling, ensuring that assessment can be carried out in a fast and reliable manner.

The decoupled methodology allows for direct extraction of both sea state limits and motion limits. Sea state limit curves can be used for planning of operations based on available forecasts, while motion limits allow real time going on location monitoring utilizing onboard motion measurement to assist with on-site decision making. A benchmark case study is presented to illustrate the improvements in the going-on-location curves that are achieved.

KEY WORDS: Jackup Touchdown, Improved Energy Method, Deterministic, Motion Combinations, Spudcan-Soil Interaction.

INTRODUCTION

During installation of a Mobile Offshore Self-elevating Unit (a.k.a. "Jackup") at a new site, the Jackup must transition from the afloat mode to elevated mode. During this transitional phase, the Jackup leg(s) will touchdown on the seabed and the associated touchdown loads are transferred through a load path consisting of the leg footing (a.k.a. spudcan), principle leg structure, leg jacking system, and eventually dissipate into the hull structure. The touchdown loads may be significant, depending upon the magnitude and combination of motions induced by the sea state (principally pitch, roll, and heave). In order to ensure safe operations, the installation event should be assessed and installation limits should be made available to the operator and rig movers.

Historically, installation limits have been defined by Jackup designers using an energy based approach to develop allowable motions. As early as 1971, Hamilton's Principle was used to derive an energy based approach for LeTourneau[1]. One of the more popular energy based methods was published in 1992 by DNV[2]. Energy based approaches are popular as they allow reasonably quick evaluations and produce consistent results, however, these approaches typically assume a rigid seabed with pure pitch or roll motions and do not consider effects of heave, hydrostatic restoration or soil interaction with the leg footing. Additionally, an allowable sea-state [which is useful for forecasting rig moves] is not commonly associated with the allowable motions. These simplifications are true of the DNVGL [3] energy based approach. Several other works have been published to address these simplifications. Notably;

- Miller et al. (1993) [4] and Smith et al. (1996) [5] presented dynamic impact analysis through time-domain simulations and two-dimensional finite element analysis to establish limiting impact loads.

- Chakrabarti (2012) [6] presented an approach consisting of a three-dimensional finite element model subjected to rigid body motions with inputs derived from Tip-Of-Can velocities. Velocities were determined by spectral analysis which utilized a Pierson-Moskowitz wave spectrum and considered Rayleigh distribution.

- Daun and Olsson (2014) [7] presented an approach comprised of a hydrodynamic model, impact model, and structural model. The methodology incorporated a coupled non-linear time-domain analysis and structural finite element analysis for evaluation of the leg and leg footing.

- Tan et al. (2015) [8] presented a coupled non-linear time-domain analysis, using commercially available software, that included simulation of a Jackup’s global motions in random sea states and the resulting leg dynamics while approaching and impacting the seabed.

- Vazquez et al. (2016) [9] presented how the leg impact loads may be related to spudcan velocity due to heave and rotational motions.

- Vazquez et al. (2017) [10] presented how the Combined Eulerian-Lagrangian (CEL) analysis can be used to account for seabed deformation effects and its energy dissipation properties after each leg impacts during touchdown.

More recently, efforts have been made to apply a fully coupled approach in order to better understand and improve installation assessments, Carre et al. (2017) [11]. This method requires a time domain simulation and due to the complexities of the method, some simplifications are still generally required. Additionally, the random nature of the touchdown event adds uncertainty when developing installation limits from the simulation results.

In order to develop consistent sea state limits using a more direct and relatively simple approach, deterministic methods have been re-evaluated. The resulting work, an improved energy approach, is presented in this paper. The proposed methodology builds on the solid base of the energy based methods and adds spudcan-soil interaction, heave motion and hydrostatic restoring effects. These improvements are incorporated while maintaining the controlled form of the energy method and utilizing detailed leg and leg-hull connection modelling, ensuring that assessment can be carried out in a fast and reliable manner.

BASIC ENERGY METHOD

The basic energy method, as described in DNVGL[3], computes touchdown impact loads based on the following assumptions.

1. The impact force is governed by rolling or pitching.
2. Only one leg touches the seabed.
3. The lower end of the leg is stopped immediately when the leg touches the bottom (i.e. the seabed is rigid)
4. The rotational energy of the Jackup is absorbed only by the leg and supporting structure.

These assumptions allow the touchdown behavior to be assessed in a very generic way without any input of the side conditions. The assumption of pure roll or pitch removes a need to carry out motion analysis, and limits may be specified in terms of allowable motions rather than seastates. The downside of the approach is that it is typically very conservative as major energy absorbing mechanisms are ignored.

IMPROVED ENERGY METHOD

The improved energy method builds on the foundation set out in the basic energy method but includes additional components to take into account the effects of spudcan-soil interaction, motion analysis including heave motion and hydrostatic stiffness of the hull. The results of the improved energy method are not limited to generation of motion limit curves but can also provide seastate limit curves which are useful for incorporation into an on-site monitoring system as well as planning of operations based on available forecasts.

The improved energy method is composed of three parts. Firstly, a hydrodynamic analysis is performed to derive Jackup's response when subjected to the design seastates. Secondly, effects of soil stiffness and spudcan design are taken into account by generating the spudcan's dynamic load-penetration behavior as representation of the spudcan-soil interaction when Jackup undergoes touchdown. Lastly, a quasi-static touchdown analysis is performed to establish the limiting motions and seastates based on the structural capacity of the Jackup leg and supporting structures. Figure 1 shows the relationship of the three parts. The decoupled form of the approach allows detailed consideration of each aspect as there are less trade-offs in modelling. For example, a detailed FEM leg model can be used to assess the structural and pinion UCs in the touchdown analysis, while a detailed hydrodynamic model is applied to generate motions.

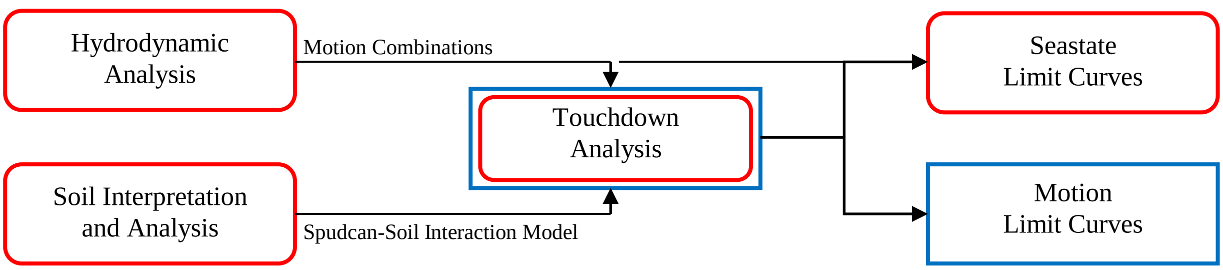

Figure 1 Improved Energy Method Flow Chart
(Blue square boxes indicate the basic energy method while red rounded boxes indicate additional components of the improved method)

- Inclusion of Hydrodynamic Analysis Including Heave Motion

In the basic energy based approach, heave motion is always ignored to simplify the analysis. However, from the collaboration works with Marin for model test and ABS for fully coupled method, it is observed that heave plays an important role during touchdown. It may however be overly conservative to apply maximum heave plus maximum rotation directly as heave may not be in phase with rotation. An example of the phase relationship of a standard Jackup for the 180 degree direction is shown in Figure 2. It is important to note the way in which the motions combine at the spudcans, for example to get a downwards vertical motion at the forward spudcan requires a negative heave to combine with a positive pitch motion. In this example, the seemingly out of phase relationship between pitch and heave at 10 seconds, is in fact close to in phase for the critical spudcan motion, while the seemingly closer phase at 5 seconds is actually further out of phase at the forward spudcan.

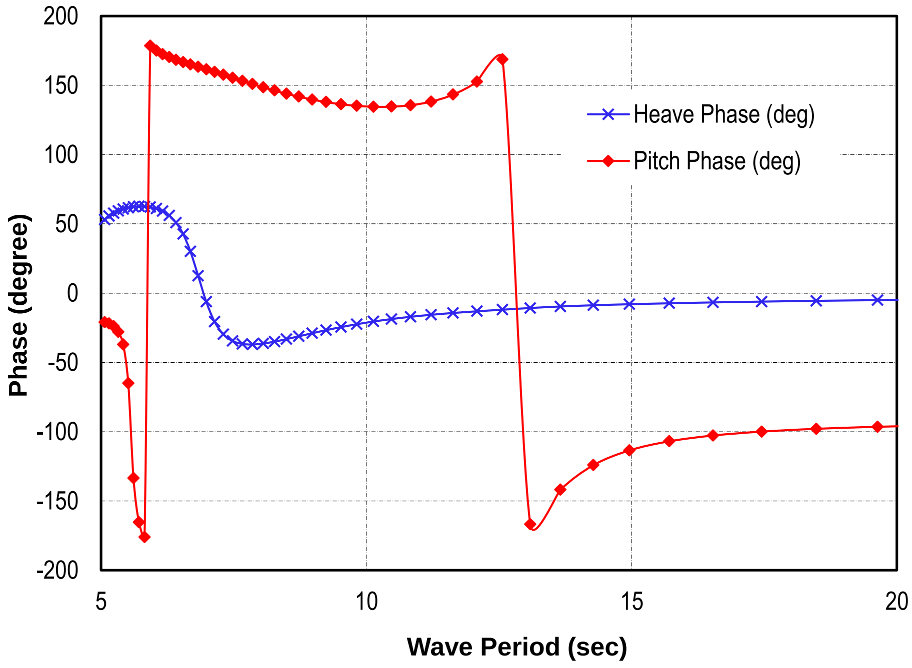

Figure 2 Heave & Roll phase angle for 90 degree wave direction

As various combinations of heave, roll and pitch can result in a variety of spudcan trajectories and impacts at the seabed, the vertical and horizontal spudcan velocities are used as a measure of combined motions. From the determined maximum spudcan motions, applicable heave and rotation combinations are generated taking into account the relative phase of the motions. Cases consisting of heave, roll and pitch motion combinations are generated based on maximum horizontal and/or vertical spudcan velocity. Subsequently, these cases are used in the touchdown analysis to determine touchdown loads and assess the structural strength of the Jackup leg and supporting structure. Figure 3 shows example of the combinations of heave and pitch for the 180 degree load direction.

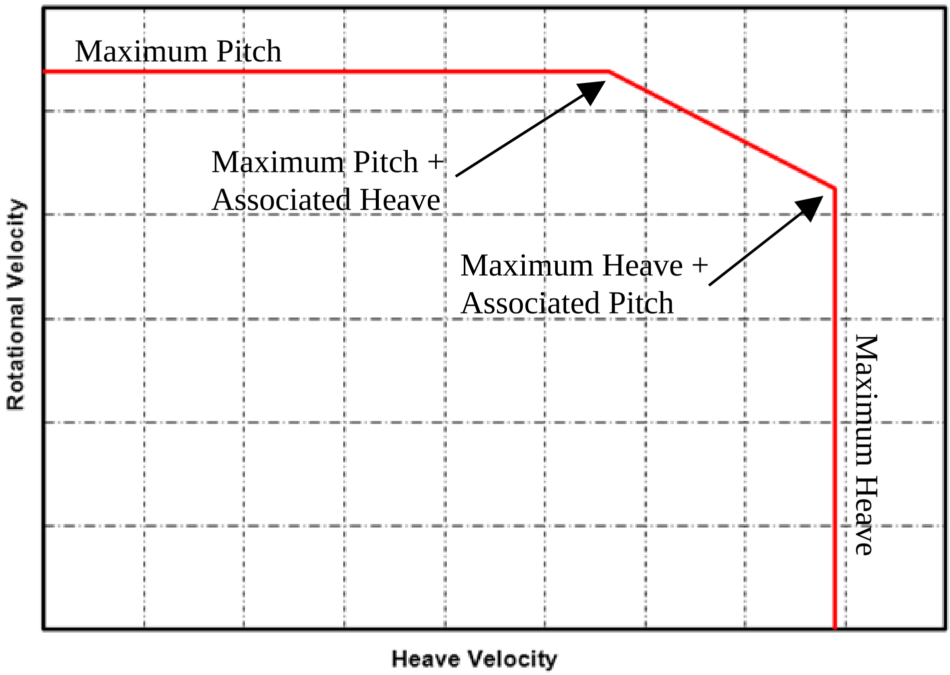

Figure 3 Example of combination of heave and pitch for 180 degree direction

- Inclusion of Spudcan-Soil Interaction

The assumption of rigid seabed is often applied as a conservative case for generic results, however when site specific soil information is available a more refined soil-structure interaction should be included in order to "soften" the impact. As the degree of softening captured in the model will have a very large impact on the results, properly capturing the correct soil stiffness for both horizontal and vertical interactions is important. In order to better understand spudcan to seabed interactions and estimate the soil properties, Keppel has participated in JIPs, such as the Wind Jack JIP, and collaborated with others such as Advanced Geomechanics and University of Western Australia. Several numerical soil models have been considered and can be used according to the specific soils encountered. Figure 4 shows an example benchmarking of a numerical model with a centrifuge test. It can be found that the numerical model agrees well with centrifuge test.

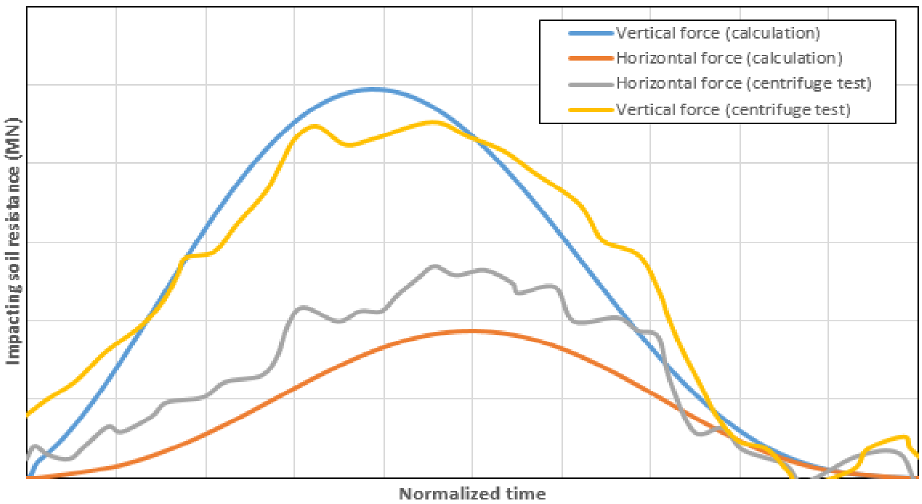

Figure 4 Benchmark of a Numerical Model with Centrifuge Test

- Touchdown Analysis Improvement

The key improvements in the final stage of the touchdown analysis are the incorporation of the hydrostatic stiffness, representation of the spudcan-soil interaction, effects of leg weight during impact and inclusion of the effects of heave. The analysis couples all of these together in order to properly assess the internal stresses in the critical areas of the legs and pinions. The inclusion of heave and spudcan-soil interaction have been discussed previously. In addition, the inclusion of hydrostatic stiffness allows the restoring forces associated with vertical and rotational motion of the hull to be captured.

The energy associated with hull restoring forces is combined with the energy absorbed in the structure and by the soil-structure interactions, to balance the total motion energy. As with a traditional energy method, displacements corresponding to the motions in each case are incrementally applied until the specified energy is absorbed by the system, at which point the utilizations are assessed. Displacements may be increased or decreased until limit utilisations are reached, at which stage the amount of energy absorbed may be compared with the energy of the input motions and the corresponding limit seastates (Hs) determined by sclaing of wave heights used in the motion analysis in order to obtain the appropriate energy. Because combined motions are assessed, the ratios of the various motions are kept constant while being ramped up. For example if a motion combination of 1m heave and 2 degrees of pitch, is assessed, the hull vertical translation and pitch motions are applied together such that 2 degrees of pitch is applied per meter of heave. As discussed earlier, the sign of the motions is carefully considered, such that the correct spudcan motion is generated. The structural analysis is conducted using a detailed leg model including guide and pinion systems, ensuring that the internal loads can be assessed without compromising accuracy.

CASE STUDY

A KFELS Jackup is selected to illustrate the methodology. The study first looks at the impact forces obtained in comparison to other methods and then illustrates the extension of the sea state limits that can be achieved in this case. For the first part of the study, the impact loads expected in 2m significant waves and a water depth of 80m are investigated for impact on a seabed consisting of firm clay. For the second part, the same water depth and soil is used but with the wave height varied to determine the allowable wave height.

In addition to the improved energy method, results from two other methods are evaluated, namely the basic energy method, as discussed earlier in this paper, and a fully coupled time-domain simulation method.

In the fully coupled time-domain simulation method employed in this paper, analysis is carried out by considering hydrodynamic responses in random sea state, structural dynamics of legs and leg-hull connections, and transient impact on seabed in a fully coupled manner. A detailed Jackup model including hull, leg and spudcan are generated using offshore marine software, OrcaFlex, with inputs of hydrodynamic coefficients (wave force RAOs, added mass matrix and radiation damping matrix) derived from WAMIT. The soil model is incorporated through a user subroutine. The need to incorporate leg lowering in determining the can elevation at the point of impact can be handled differently in various coupled approaches, see Tan et al. (2015) [6]. For this study, simulations using various fixed spudcan elevations were used and the maximum forces from 3 hour storms extracted. This method has been found to give comparible results to other approaches. For this study, three random wave seeds and three spudcan elevations are used for each selected period to generate 9 simulations per period, and the results observed to see whether additional elevations were required in order to capture the maximum cases.

To derive the inputs for each method described in the case study, a frequency-domain diffraction analysis is carried out using WAMIT to calculate the motion RAOs, added mass, natural periods and hydrodynamic stiffness. The model of the Jackup and corresponding motion RAOs curves from the diffraction analysis are shown in figures 5 and 6.

In this study, a reasonably simple soil model is determined for the firm clay seabed with resulting vertical and horizontal load curves as shown in figure 7. It is noted that the tip of the spudcan creates a very soft initial section on the soil-structure interaction curve. Internal procedures are used in the analysis to account for this "soft tip".

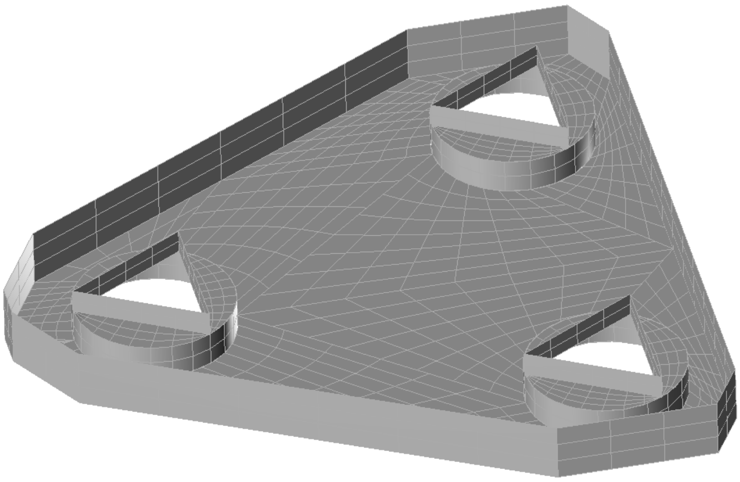

Figure 5 Diffraction Model of the Jackup

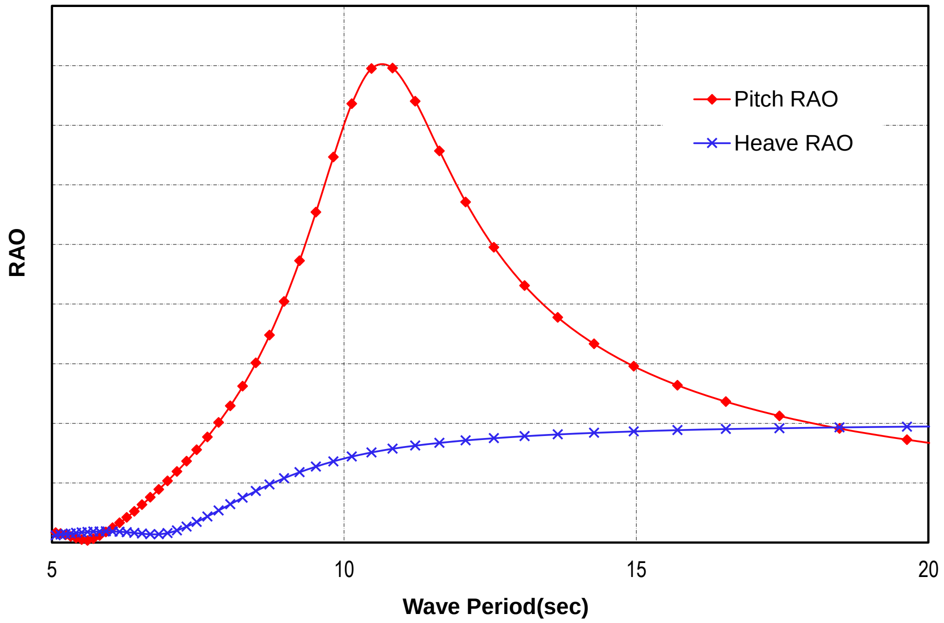

Figure 6 Motion RAOS for 180 degree direction

Vertical and horizontal impact results from the three methods are shown in figures 8 and 9. For the case study, structural response on various wave headings are investigated. However, only the most critical (180 degree) wave heading is presented.

While for the energy method, the deterministic form allows direct generation of design values, the random nature of the time domain simulations for the fully coupled method mean that judgment is needed on the number of seeds to run and on how the design values should be extracted. As the analysis time and number of cases to be considered is large, in this example we have limited the number of 3hr storm runs for each wave period, to three random seeds and at three spudcan elevations, and have provided results for comparison), at only three wave periods, namely 8, 10 and 12 sec.

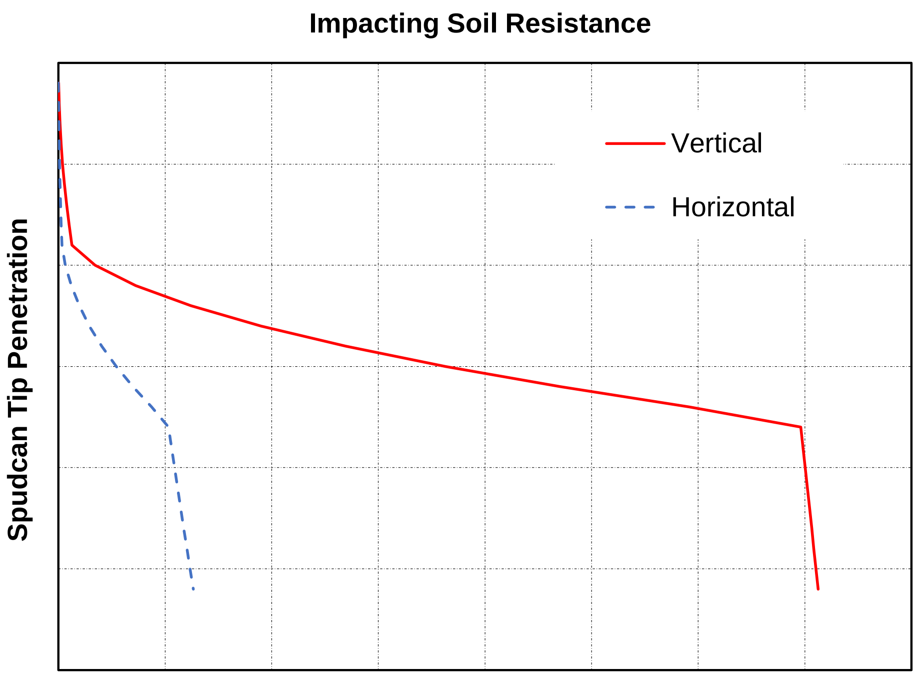

Figure 7 Soil Load-Penetration Impact Curves

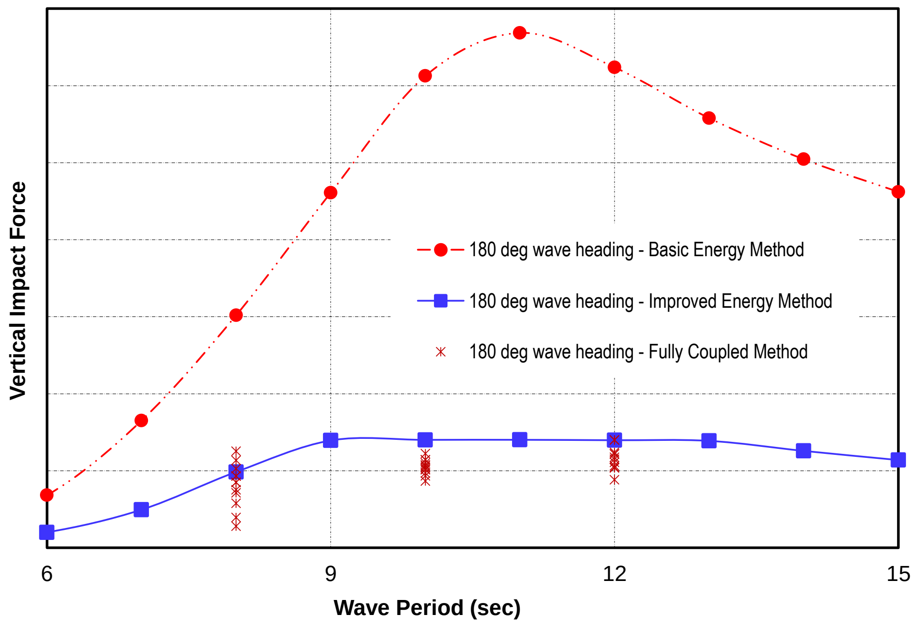

Figure 8 Vertical Impact Force Comparison

From figure 8, as expected, it is clear that the basic energy method generally produces much larger vertical impact forces, while the improved energy method and the maximum result of the coupled analysis runs produce quite similar load levels. In this example this can be partly attributed to the vertical soil resistance having a "drop off" where the maximum spudcan area is reached. A similar trend is observed in other cases however and the fact that the coupled analysis results typically do not reach this value is some indication that the "drop off" is not the main driver affecting the results.

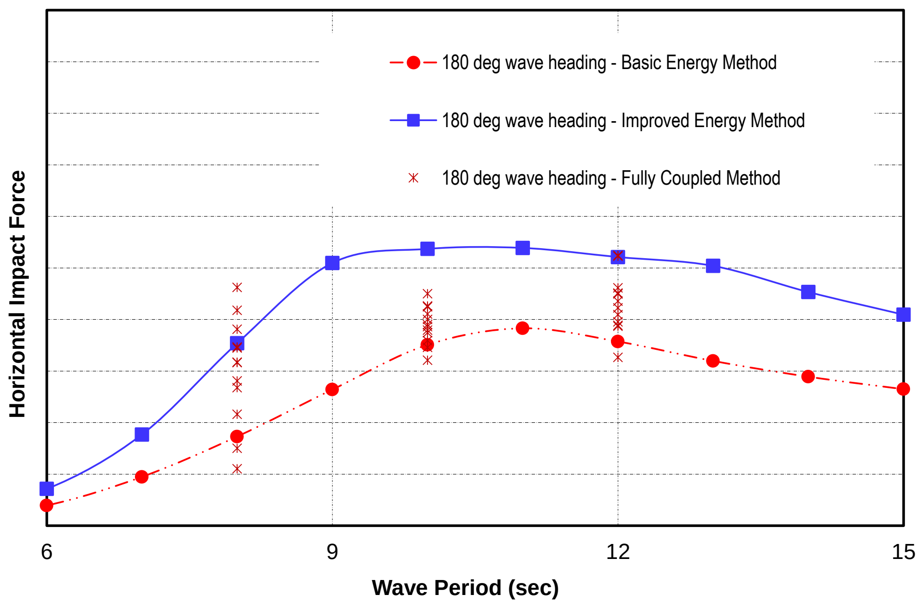

Figure 9 Horizontal Impact Force Comparison

Figure 9 illustrates the horizontal impact forces obtained. It is interesting here to observe that, due to the very stiff vertical impact generated by the rigid seabed of the basic energy method, the horizontal impact is in fact underestimated in comparison to the improved energy method and the fully coupled method. Again the loads generated using the improved energy method and the maximum load from the fully coupled method are comparable. In this case the same soil-structure interaction model is incorporated in both methods through user subroutines. As a large part of the load in the pinions can be attributed to lateral loading, this indicates that inclusion of proper lateral and vertical soil-structure stiffness is important.

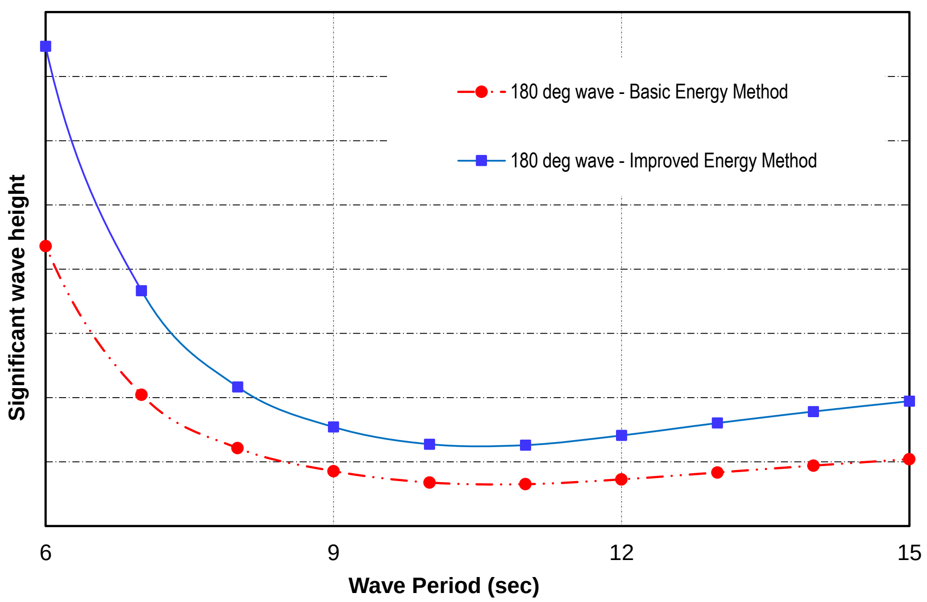

Figure 10 Allowable Sea State Limit Curves

Figure 10 shows the series of curves representing the sea state limits for basic energy method and improved energy method. Results for fully coupled method are not generated here as iterations are required in order to rerun analysis and selection of the limits from the results is open to wider interpretation. It is observed that, due to the additional energy mechanisms incorporated. The sea state limits resulting from the improved energy method are consistently higher than the basic energy method.

APPLICATIONS OF IMPROVED ENERGY METHOD

- Sea State Limit Curve

Using the improved energy method, sea state limits, such as those depicted in figure 10, can be generated at for each wave direction. These sea state limit curves can be used by operators to identify suitable weather windows for the rig installation operation with reference to suitable weather forecasts.

- Motion Limit Curve

In addition to sea state limit curves, because the motion analysis is decoupled from the touchdown analysis, the improved energy method can also conveniently provide allowable motion curves which include maximum allowable heave, roll and pitch amplitude for each wave period and wave direction. In addition to "pure" motion curves, as the combinations of heave, roll and pitch are considered, the results of the analysis are able to be integrated into the OTD rig move monitoring system [12] which internally combines the effect of heave to adjust the allowable motion curves which are output, together with present motion levels, as a guide to operators. In addition to the forecasting carried out using the sea state limit curves, the operator can then validate the decision to proceed based on the measured motion levels. Figure 11 provides an example screenshot of how the motion limit curves can be utilised to aid operators.

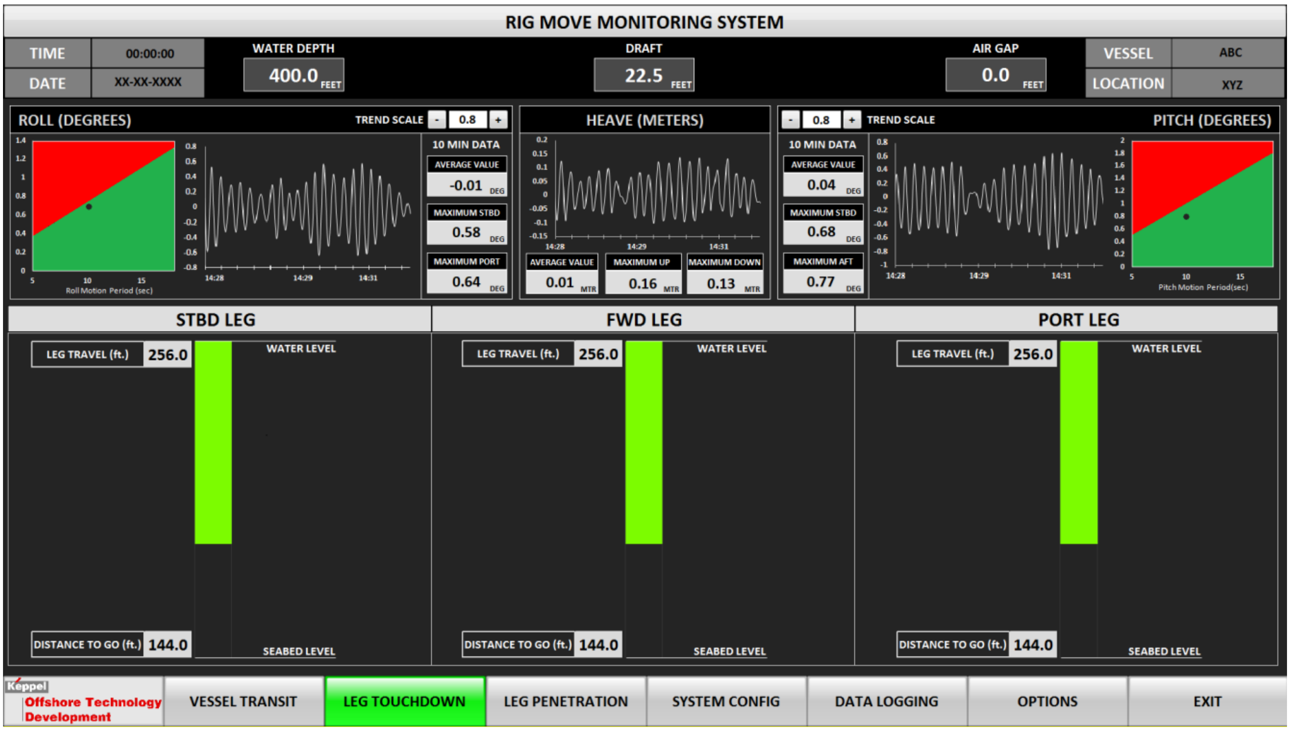

Figure 11 – OTD Rig Move Monitoring System

CONCLUSIONS

A desire to provide direct, repeatable, generation of sea state limits, has driven a relook of deterministic methods and development of the enhanced form of the energy method presented in this paper. Building on the basic energy method which assumes impact force to be governed only by rolling or pitching, the improved energy method also includes a hydrodynamic analysis to properly incorporate the contribution of heave motion. Furthermore, it minimizes the extensive conservatism by taking into account additional energy dissipation factors by appropriately representing the spudcan-soil interaction as well as the hydrostatic restoring of the hull.

As seastate and motion limits are developed in parallel, seastate limits can provide owners with the ability to plan and forecast operations, while the motion limits can be incorporated into onboard monitoring systems to provide additional information to operators.

The case study results demonstrate the significant gains that can be realized over basic energy approaches, incorporating more realistic motions and interactions while maintaining fast, deterministic performance that ensures repeatable results that can be directly extracted to provide limits to operators.

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REFERENCES

[1] Engineering Technology Analysts, A Computer Program for the Calculation of Safe Sea Conditions for Elevation of a Self-Elevating Mobile Drilling Unit, 1971

[2] DNV Classification Notes 31.5 – Strength Analysis of Main Structures of Self-Elevating Unit, Det Norske Veritas, 1992.

[3] DNVGL-RP-C104 Ed. July 2015 – DNV-GL Recommended Practice Self-elevating units – Rules and standards, DNV GL AS, 2015.

[4] Miller BL, Frieze PA, Lai PSK, Lewis TC, Smith IIA, Motions and Impact Responses of Jackup Moving onto Location. In: Proceeding of the 25th Offshore Technology Conference (OTC), Houston, Texas, 1993.

[5] Smith IIA, Lewis TC, Miller BL, Lai PSK, Frieze PA- Limiting Motions for Jack-ups Moving onto Location, Marine Structures. 1996:9 (1): 25-51.

[6] Chakrabarti P, Going on Location Study for a Jack-up Rig. In: Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Rio de Janeiro, Brazil, 2012.

[7] Daun V, Olsson F, Impact Loads on a Self-elevating Unit during Jacking Operation. Master's Thesis, Department of Shipping and Marine Technology, Chalmers University of Technology, Göteborg, Sweden, 2014.

[8] Tan P, Chen X, Yu Q, Perry M, Mu H, Chang T, Wong M, Chen D, Jackup Going On Location Analysis. In: Proceedings of the 15th International Conference on the Jack-up Platform Design, Construction & Operation, London, UK, 2015.

[9] Vazquez J, Grasso B, Gamino M, Wang W, Jackups Going On Location – Understanding Energy Principles on Leg Impact Loads. In: Proceedings of the 21st Offshore Symposium, Houston, Texas, 2016.

[10] Vazquez J, Grasso B, Gamino M, Templeton J, Using CEL To Account for Seabed Deformation Effects for Jack-Ups Going On Location. In: Proceedings of the 22nd Offshore Symposium, Houston, Texas, 2017.

[11] Carre D, Mcarthur L, Simpson A, Zhang P, Vazquez J, GSF Galaxy I Jackup Case Study for Optimizing Rig Move Performance in North Sea using an Advanced Simulation Model. In: Proceedings of the 22nd Offshore Symposium, Houston, Texas, 2017.

[12] Foo KS, How B, Mu H, Perry M, Abidi S, Quah M, Jackup Rig Move Support: Real-time Monitoring, Data Interpretation and Simulation. Technology Review, 2015.