GOING-ON-LOCATION OF JACK-UPS: A COMPREHENSIVE FRAMEWORK FOR SITE-SPECIFIC ASSESSMENT OF INSTALLATION

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ABSTRACT

This paper presents a comprehensive framework for simulation of going-on-location (GoL) of jack-ups. The GoL operation is the transition of a jack-up from a free-floating state to a bottom-founded state.

Current recommended practice requires using site-specific operability limits for GoL, but does not provide guidelines for determination of these limits. The presented framework provides general guidance for creating suitable models.

The framework enables fully decoupled, independent modeling of hydrodynamics, structural behavior and soil-spudcan interaction. This ensures that the level of complexity and modeling choices in one area of expertise do not influence the other. This flexibility is enabled by representing the jack-up as a multi-body structure, where the hull and spudcans are separate entities, each with its own properties. This is the key difference from most state-of-the-art approaches, where a rigid-body assumption is used and all constitutive relations are necessarily combined in a single simplified relation.

Site-specific models adhering to the presented framework, where all bodies are independently governed by the equation of motions, are suitable for time domain simulation in order to determine the structural loading that limits the operability.

A model implementation adhering to the framework is described, outlining the three main elements. The hydrodynamic and structural model implementations are straightforward. A soil-spudcan interaction model implementation, which includes elasto-plastic behavior and coulomb friction, is implemented to model non-linear soil resistance to both spudcan penetration and lateral displacement for sandy seabeds. It incorporates aspects of kinematic hardening by taking into account stateful characteristics and includes damping through hysteresis. This complex model is selected to showcase the flexibility of the framework. A sample simulation is presented at the end of the paper.

As the presented framework facilitates effortless exchange, implementation, or modification of soil behavior theories and jack-up models, it enables establishing site-specific installation limitations.

KEY WORDS: Going-on-location, site-specific operability, soil-spudcan interaction

INTRODUCTION

Going on location

Jack-ups used in the offshore industry frequently relocate in varying conditions. A jack-up installation involves the transition from a free-floating state to a bottom-founded state. This transition is referred to as the going-on-location (GoL) or installation operation.

During the GoL operation, the legs are continuously lowered at a more or less constant, low velocity. In the initial, free-floating phase, there is no contact between the spudcans and the seabed. During the second phase, the impact phase, the contact between the spudcan and the soil occurs intermittently. In the final, soft-pinned, phase, the spudcans are in continuous contact with the seabed and horizontal and vertical motions are restricted by soil resistance.

The impact phase starts when the first soil-spudcan interaction occurs and ends when permanent contact between the soil and the spudcans has been established. During the impact phase, subsequent axial and lateral impact forces act on the spudcan due to its vertical penetration and lateral displacement, while in contact with the soil. These impact loads influence the vessel motions and contribute to loading in the leg.

During the soft-pinned phase, the hull is still partly in the water and can be subject to significant hydrodynamic loading. Particularly for larger water depths, the structural loading in this phase can be even more severe than during the impact phase.

Leg loads are compared to load capacities to determine operability. In order to determine site-specific operability for GoL, a site-specific simulation model is needed. Such a model should, ideally, be suitable to simulate all three phases of GoL.

Site-specific simulation models

Current recommended practice [4] requires a Site-Specific Assessment for Installation (SSA-I), including site-specific operability limits, to be used for planning and on-board decision-making for the GoL operation. In many cases though, in lieu of site-specific operability limits, limits according to the Marine Operations Manual (MOM) are used [10][11]. These limits are based upon jack-up specific models, for generalized conditions [1] as opposed to site-specific conditions.

Determination of site-specific operability limits will increase the understanding of jack-up behavior for site-specific conditions [12][13], and supersede limits in accordance with the MOM [4].

To determine site-specific operability limits, simulation models that incorporate site-specific factors such as soil conditions, water depth, and loading condition of the jack-up are required. Guidelines as per current recommended practice [1] does not specify how such models should work [5].

The comprehensive framework presented in this paper provides general guidance for creating suitable models. The framework facilitates the exchange, implementation, or modification of soil behavior theories, jack-up specifications and sea state parameters. Models adhering to the framework are suitable for time-domain simulation of GoL to establish site-specific operability limits.

FRAMEWORK FOR SITE-SPECIFIC SIMULATION MODELS

The framework serves as a general approach for creating models suitable for simulation and analysis of the going-on-location operation, to establish site-specific operability limits. It combines a hydrodynamic model, a structural model of the jack-up, and a soil-spudcan interaction model into an integrated model.

The key aspect of the framework is marked by the independence of the three components, enabled by a multi-body structural representation of the jack-up. Traditionally, jack-up representations in simulation models for going-on-location, often employ a rigid-body jack-up design, incorporating multiple critical aspects including leg bending, leg-hull interface compliance and soil behavior within a single equivalent element. The complexity of such equivalent elements is necessarily high and the accuracy relatively low.

The multibody jack-up representation, according to the framework, describes the spudcans and the hull as distinct bodies, each characterized by their own properties. The multi-body approach enables the decoupling of the areas of expertise, allowing them to be addressed separately.

Models adhering to the framework, are able to capture the distinctly transient behavior of the jack-up during GoL. Therefore time-domain simulations are the most suited approach. Each body is independently governed by the equations of motion (EOM), for which the motions are determined as a result of applied and resulting force in time.

In the following sections, a brief introduction to each of the three components, outlining their individual contributions within the framework, is followed by an implementation example. A complex soil-spudcan interaction model has the focus.

HYDRODYNAMICS

Hydrodynamic component within the framework

The motion analysis of a jack-up involves evaluating both the hydrodynamic loading on the hull and on the spudcans. The hydrodynamic properties of the hull can be determined through diffraction analysis. For each of the spudcans an individual hydrodynamic model is implemented with its own properties, which could be based on diffraction or frequency independent values. The legs are best addressed by equivalent-stick Morison elements.

Hydrodynamics implementation

The hydrodynamic model is implemented in OrcaFlex[6]. OrcaFlex, simulation software developed by Orcina, is extensively used within the offshore and maritime sectors for the dynamic analysis and design of systems. It enables straightforward implementation of hydrodynamic models and has a strong and flexible interface for C++ and Python scripts to model complex loading behavior.

The hydrodynamic properties of the hull include the hydrostatic stiffness, along with frequency-dependent added mass and damping, and wave forces. In this implementation wave loads are governing over wind and current forces, which therefore are ignored. Provisions are included to address the change in hydrodynamic loading due to draft reduction in later phases of GoL.

The spudans are modelled as separate rigid bodies with drag and inertia coefficients. The legs are modelled as line objects connecting the spudcans to the hull employing the Morrison equation. (In this approach, the legs are discretized to connected elements, each individually governed by the EOM, therefore significantly expanding the number of bodies in the model.)

An additional improvement to the hydrodynamic implementation could be the inclusion of frequency-dependent added mass coefficients for the spudcans. This could be particularly relevant as second or third order effects may evolve when the spudcan is near the seabed during the leg-lowering phase [2].

JACK-UP STRUCTURE

Jack-up structure within the framework

In the multi-body representation of the jack-up, the spudcans and the hull are modelled by separate rigid bodies, interconnected by a structural representation of the jack-up. A bar-stool model, equivalent to most models used for site-specific assessment in elevated condition (SSA-E) [3], is most suitable.

The first objective of the structural jack-up representation is to address the internal force equilibrium within the system i.e., to ensure that the spudcans are fixed to the hull with some level of flexibility.

The second objective is to determine the internal structural loads that can be compared to the structural limits in order to determine operability.

Jack-up structure implementation

The four cylindrical legs are represented by beam elements and connect the spudcans to the hull. These are modeled as *line* elements in OrcaFlex and obtained from the Calypso model suitable for SSA-E [8]. The beam elements have bending and axial stiffness. The spudcan-leg and the leg-hull connections are modelled rigidly.

A recommended enhancement of the structural component involves incorporating a more complex leg-hull interface. By addressing flexibility, including backlash and the guide gap, a more realistic representation can be achieved.

SOIL-SPUDCAN INTERACTION

Soil-spudcan interaction within the framework

The multi-body approach enables the incorporation of complex soil-spudcan interaction models. A soil-spudcan interaction model adhering to the framework, calculates the soil-induced force acting on the spudcan, as a function of spudcan displacement and/or velocity and any other factors. It can be stateful i.e., have memory.

Soil-spudcan interaction implementation – introduction

In this section, a displacement-dependent, stateful implementation soil-spudcan interaction model is outlined.

Given the different behaviors and characteristics of vertical and horizontal soil reaction, these are modelled separately, both considering elasto-plastic theory. The horizontal resistance is dependent upon the vertically applied force on the spudcan.

Within the elasto-plasticity theory, total soil deformation is divided into two types: recoverable and permanent deformation. The soil exhibits primarily plastic (permanent) deformation, governing over elastic (recoverable) deformation [9][11]. The following sections detail the application of elasto-plastic theories to both vertical and horizontal soil reaction paths for a conical spudcan in a flat, uniform, sandy seabed. These are applied in OrcaFlex as external Python scripts, called at every time step to calculate the forces acting on the spudcan bodies.

Soil-spudcan interaction implementation – Vertical reaction

The bearing capacity theory is the recommended approach for the prediction of vertical soil resistance [3]. This theory is used to describe the resistance for vertical penetration of the soil by the spudcan, independent of velocity.

Four penetration modes are distinguished: (1) no soil contact, (2) virgin soil penetration, (3) unloading, and (4) reloading. These modes enable elasto-plastic soil behavior while the spudcan undergoes subsequent vertical penetration cycles. The bearing capacity theory is the backbone for the vertical resistance path for the virgin soil penetration. For unloading and reloading a modulus, K, is adopted to address the recoverable (elastic) part of the deformation. The soil resistance is zero when there is no soil contact, taking into account plastic deformation of the soil below the spudcan.

The left part of Figure 1 illustrates a vertical soil reaction path for penetration. During the initial penetration into the untouched soil, or virgin soil penetration mode (2), the soil resistance is governed by the bearing capacity theory. At the onset of unloading, mode (3), the resistance decreases by a linear modulus K, until resistance is reduced to zero. Beyond this point the spudcan is still below the seabed but has lost contact with the soil, mode (1), signifying plastic deformation of the soil below the spudcan. When the spudcan repenetrates, mode (4), the resistance increases along the same linear path as for unloading. If the historic deepest penetration is exceeded, again mode (2) for virgin soil penetration is active.

A memory term is included in the vertical soil-spudcan interaction model, to account for the plastic, or permanent deformation. The ability of the yield surface to expand without translation exhibits characteristics of isotropic hardening [7]. This form of strain-hardening leads to hysteretic damping.

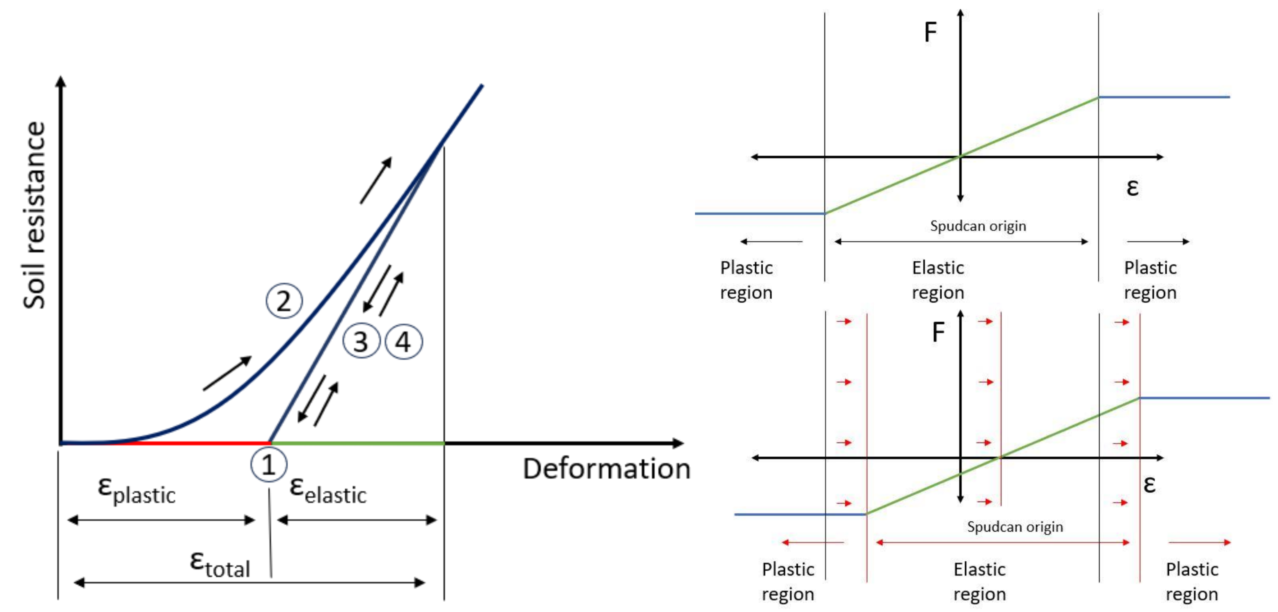

Figure 1 – Vertical soil reaction path *Horizontal soil reaction path*

Soil-spudcan interaction implementation – Horizontal reaction

The total lateral soil resistance consists of two contributions: the side resistance, and the frictional resistance acting on the spudcan's bearing area.

Passive soil pressure counteracts the spudcan's lateral displacement towards a soil mass, while active soil pressure fills the gap as the spudcan moves away from a soil mass. The friction resistance arises due to the interaction between soil particles and the spudcan's bearing area, creating a force that opposes the spudcan's lateral movement. The friction is dependent upon the instantaneous vertical load.

The horizontal soil resistance (both contributions) exhibits a stick-slip mechanism. The spudcan initially deforms the soil elastically, and, as the applied displacement exceeds the yield criterion, the spudcan slides and plastically deforms the soil. A yield criterion separates the elastic and plastic soil deformation regions. The upper graph in the right part of Figure 1, indicates the elastic and plastic regions within which the origin of the yield surface is positioned midway between the left and right yield surface, i.e., the vertical black lines. When the spudcan is at this origin, the horizontal force is zero.

When horizontal displacement increases, the horizontal reaction force increases, until the yield criterion is exceeded. When this happens, the reaction force remains constant and the yield surface shifts along with the spudcan, as presented in the bottom graph of the right part of Figure 1.

The ability of the yield surface to translate without changing in size exhibits characteristics of kinematic hardening [7]. As for the vertical reaction model, this form of strain-hardening leads to hysteretic damping.

Soil-spudcan interaction implementation – Potential improvements

Impact forces, by nature, involve short time scales. The soil experiences rapid loading such that there is not adequate time for water to either seep into or flow out of the soil pores, which is undrained behavior as opposed to the drained behavior assumed in the bearing capacity theory. The incorporation of velocity-dependent parameters could improve soil modelling during impact events.

The framework setup facilitates implementation of various soil behavior theories for different soil types, including loading rate. The complex implementation presented in this section showcases the suitability of the framework for implementing complex soil-spudcan interaction models.

EXAMPLE SIMULATION

Introduction

In the previous section, the implementation of each component of the framework was presented. Models adhering to the framework are able to incorporate site-specific parameters into a time-domain analysis. In this section, a demonstration of a single simulation in OrcaFlex is presented. The chosen simulation serves as an illustrative example to showcase the capabilities of the framework under realistic moderate environmental conditions. The objective of the simulation is to analyze the impact forces on the spudcans during the impact phase of the going-on-location process. Figure 2 shows the model.

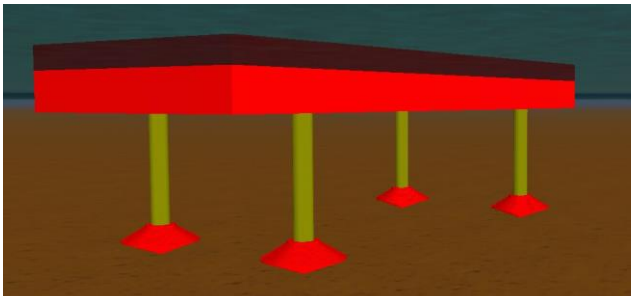

Figure 2 – Graphic representation of the model

Input parameters

The jack-up is subjected to irregular waves, with a significant wave height of 1.5 m and a period of 8 s. The heading of the waves is 90 deg, representing beam seas. The water depth is 35 m.

For the seabed, a medium-dense sand with a friction angle of 35 degrees and an effective unit weight of 11 kN/m^3 is used. The flat seabed consists of uniform sand.

A medium-sized jack-up commonly used in the offshore wind industry is selected. The vessel is equipped with four cylindrical legs, each characterized by specific axial and bending stiffness values. The legs have a constant leg-lowering rate. The spudcans are conical.

A time-domain simulation of 500 s was conducted, with a real time evaluation of approximately 90 s on an engineering laptop.

Results

Figure 3 (final page) illustrates the results of the simulation, with the upper graph showing the axial forces acting on the four spudcans over time. The lower graph displays a time trace of the sea elevation.

The going-on-location operation consists of three distinct phases: free-floating phase (I), impact phase (II), and soft-pinned phase (III), see Figure 3. Time domain simulations using models adhering to the framework go through these phases in sequential order. The complete simulation of all three phases is characterized by its transient nature. This is attributed to the gradual lowering of the legs, the interaction between the soil and spudcans, and the establishment of draft reduction during the soft-pinned phase.

Verification

The first (free-floating) phase and final (soft-pinned) phase of the transient simulation can be approximated by simple stationary models, to verify the behavior of the transient model.

The vessel motions in the free-floating phase of the full transient simulations were compared to those of a stationary free-floating model and were found to be identical [5]. Similarly, forces acting on the spudcans during the soft-pinned phase of the full transient simulation were compared to those of a stationary soft-pinned model. A soft-pinned model is identical to the simulation model, but with the soil-spudcan interaction model replaced by a pinned connection. The comparison again shows a high level of similarity [5].

It is shown that the first phase and final phase of the transient simulation are identical to the stationary models. This indicates that the transient simulation model starts correctly and develops to the expected final condition.

CONCLUSION

This paper introduces a comprehensive framework that integrates a hydrodynamic model, a structural jack-up representation, and a motion-dependent soil-spudcan interaction model. These three components can be developed independently, because of the multi-body modelling approach. The framework enables engineers to create an accurate, site-specific model for simulation of the going-on-location operation.

The simulation results of models adhering to the framework enable risk assessment and operability analysis, to support planning and on-board decision-making. As opposed to the operability limits in the Marine Operations Manual, this approach considers site-specific parameters.

The capability to determine site-specific operability limits and assess the risks associated with the going-on-location operation can significantly enhance operational efficiency and effectiveness of jack-up operations throughout the offshore industry.

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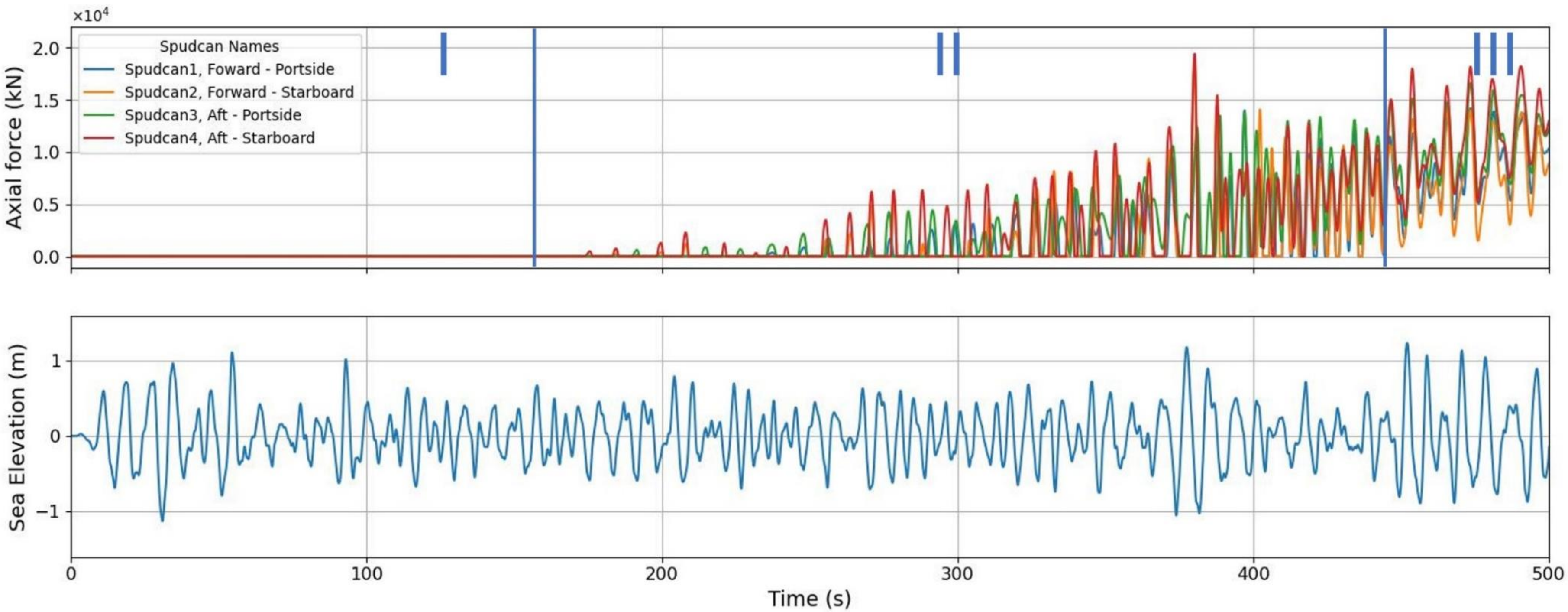

Figure 3 – Simulation result graphs. The upper graph presents the axial impact forces exerted on the spudcans, considering the three distinct phases: free-floating phase (I), impact phase (II), and soft-pinned phase (III). The lower graph presents a time trace of the wave elevation.