JACK-UP MOTION RESPONSE AND LEG TO SEABED IMPACT LOADS DURING INSTALLATION AT SITE: COMPARISON OF MODEL TESTS AND SIMULATIONS

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ABSTRACT

In the present paper a comparison is made between seabed impact loads on legs of a jack-up and the jack-up's motion response during siting operations from physical scale model tests and two time domain simulation models, in order to demonstrate the capability of the numerical models to predict the impact loads and motions. In the physical scale model tests as well as in the numerical time domain models a coupled hydrodynamic-geotechnical approach is followed including the jack-up vessel, its legs and representation of the seabed characteristics. The results presented in the paper show that both numerical models are capable to predict the impact loads on the legs of the jack-up with satisfactory accuracy.

KEY WORDS: jack-up, seabed, impact, installation, simulation, model test, hydrodynamics.

INTRODUCTION

The seastate in which a jack-up platform can be installed at site is typically limited by the impact loads on the legs or spudcans during touch-down onto seabed. A good understanding of this process and an accurate prediction of these loads are essential to determine the maximum wave conditions in which the siting operation (i.e. the positioning of the jack-up on the seabed) can safely be performed. State-of-the-art methods to predict the leg to seabed impact loads are time domain simulations comprising a hydrodynamic model of the floating jack-up, a structural model of the jack-up and its legs and a geotechnical model describing the leg to soil impact.

A joint industry project, the WindJack JIP, has been executed aiming to understand and predict the leg to seabed impact loads during siting operations. Numerical time domain simulation models have been developed by MARIN and GustoMSC independently to predict these impact loads. The numerical models are tuned and validated by results of physical scale model tests. Geotechnical (Deltares) and wave basin model tests (MARIN) have been performed for a typical four-legged wind turbine installation jack-up platform. The motion response of the jack-up and the impact loads on the legs were measured for various wave conditions, leg positions and seabed characteristics. A selection of model tests as performed in the wave basin has been reproduced by time domain simulations. In the simulations, the exact same wave conditions, mass properties and soil model as achieved during the basin tests has been applied. This allows for a one-to-one comparison of the model test and the two series of simulation results.

METHODOLOGY

In order to understand and predict seabed impact loads on the legs of jack-up type wind turbine installation vessels at the moment of touch-down, the WindJack Joint Industry Project (JIP) was initiated in 2011 by MARIN and Deltares. A total of 11 industrial partners, amongst which GustoMSC, participated in this JIP. To predict the seabed impact loads on the legs at the moment of touch-down, a time domain simulation model (aNySIM) was developed within the course of the JIP, consisting of a hydrodynamic representation of a jack-up and its legs and a geotechnical module to compute the seabed impact loads. The coupled numerical model is capable of calculating the hydrodynamic motion response of the jack-up taking into account the seabed impact loads on the legs.

The final geotechnical module to compute the seabed impact loads is based on geotechnical centrifuge tests and (dynamic, large strain) numerical simulations with the Anura3D code (Ref [1]) for typical spudcan shapes and realistic sandy seabed conditions. Coupled hydrodynamic-geotechnical model tests including representation of the jack-up, its legs and the interaction with the seabed were performed to validate the coupled numerical model.

During the course of the project different geotechnical models were developed and coupled to the hydrodynamic jack-up model:
1) Initial Simplified Soil Model (SSM);
2) Advanced Soil Model (ASM) based on geotechnical centrifuge tests and Anura3D simulations;
3) Artificial simplified soil model as applied in the hydrodynamic model tests.

A schematic representation of the followed methodology is shown in Figure 1.

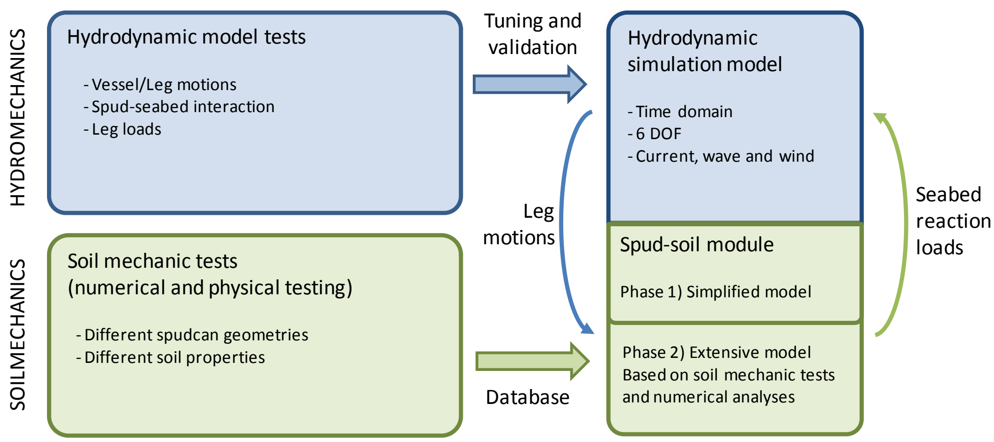

Figure 1: schematic representation of the WindJack JIP methodology

Already since the eighties, GustoMSC has been developing its own time domain simulation model (LIMP) to calculate the hydrodynamic motion response of jack-ups including seabed impact loads. This program has been used extensively for many jack-up designs and site specific analyses.

In the present paper the results of both numerical models (aNySIM and LIMP) are compared to the results of the physical coupled hydrodynamic-geotechnical model tests.

WAVE BASIN MODEL TESTS

A dedicated model of a typical, barge shaped, four-legged jack-up has been manufactured for the model tests at a geometrical scale ratio of 1 to 30. The main particulars of the jack-up are presented in Table 1. An impression of the jack-up is given in Photo 1.

Designation	Magnitude
Length between perpendiculars [m]	115.00
Breadth [m]	45.00
Draft [m]	5.20
Trim [deg]	0.00
Displacement [ton]	25,973
Vertical centre of gravity [m]	14.51
Roll radius of gyration [m]	20.45
Pitch radius of gyration [m]	32.70
Yaw radius of gyration [m]	32.08
Roll natural period [s]	11.8
Pitch natural period [s]	8.2

Table 1: Main particulars of the jack-up (for legs lowered 23.8 m below the hull / 1.0 m clearance)

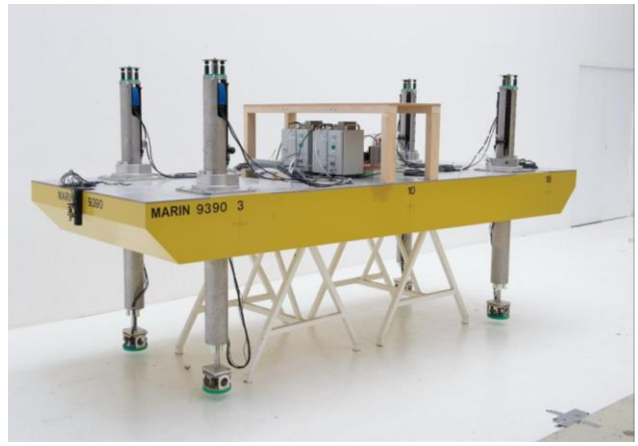

Photo 1: Impression of the jack-up model used in the hydrodynamic model tests

The vertical seabed stiffness characteristics were modeled by means of four linear actuators, one installed in each leg. Alternative approaches to model the seabed characteristics by means of physical soil or mechanical springs and dampers installed on the basin floor have been considered. The approach to model the seabed characteristics by means of linear actuators installed inside the legs has been selected to give maximum flexibility in the representation of the seabed characteristics and maximum transparency in the penetration of the leg tips into seabed and associated seabed impact loads.

The integration of the actuators inside the legs is shown in Figure 2. A schematic representation of the actuator control loop is given in Figure 3.

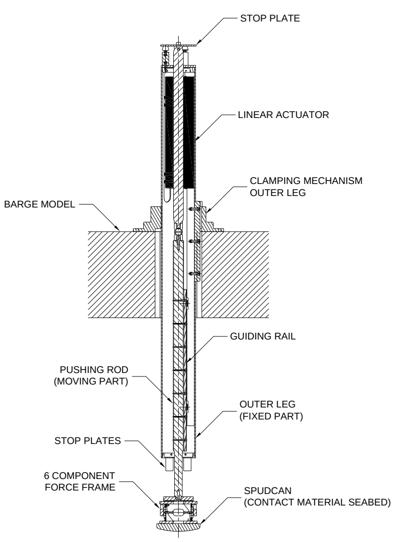

Figure 2: Integration of linear actuator inside each leg

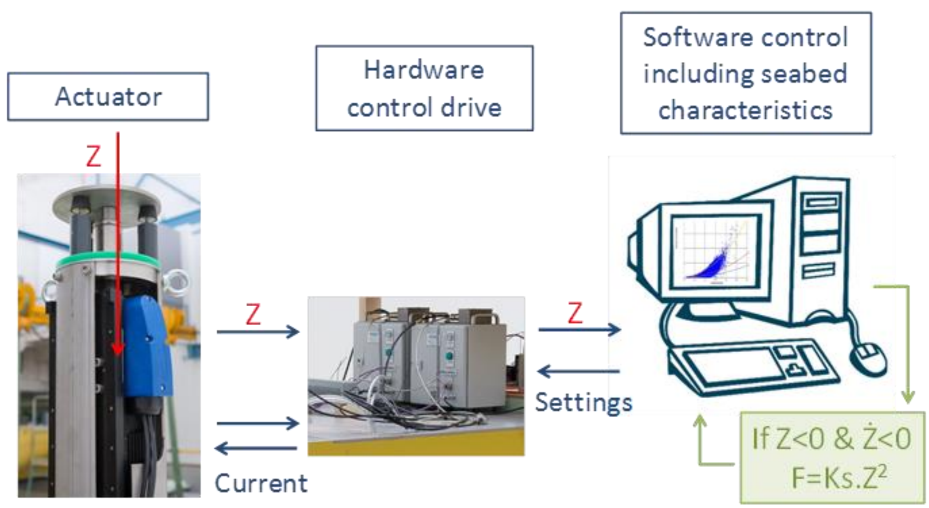

Figure 3: schematic representation of actuator control loop to represent the vertical seabed stiffness

The linear actuators were software controlled to deliver a seabed reaction force quadratic to the spudcan penetration depth during penetration of the spudcan into the seabed only. As such, energy from the jack-up is dissipated into the seabed. The seabed reaction force was programmed as follows (artificial simplified soil model):

$$F_z = K_s . z^2 \qquad \text{if } z < 0 \text{ and } \dot{z} < 0 \qquad \text{[Eq. 1]}$$
$$F_z = 0 \qquad \text{if } z \geq 0 \text{ or } \dot{z} \geq 0$$

Where:

F_z : Vertical seabed reaction force [kN]
K_s : Vertical seabed response parameter [kN/m^2]
z : Penetration of spudcan into the seabed [m]

The vertical seabed response represented in the model test was selected based on the initial predictions from the Simplified Soil Model and results of the geotechnical tests available at the time of the hydrodynamic model tests. Seabed stiffnesses in the range of 10 to 100 MN/m^2 have been applied in the hydrodynamic model tests, represented loose to medium dense sands under undrained (short duration) loading conditions. Under these conditions the reaction force on a tapered (conical) spudcan is approximately proportional with the spudcan - seabed contact area and thus with the square of the penetration depth. Note that the response is mainly plastic with a very limited elastic rebound.

A typical time trace of the seabed reaction force generated by the actuator is shown in Figure 4 for a seabed stiffness K_s=50 MN/m^2. The results presented in the figure show that the actuator only delivers a reaction force in case of penetration of the spudcan into the seabed ($z < 0$ and $\dot{z} < 0$).

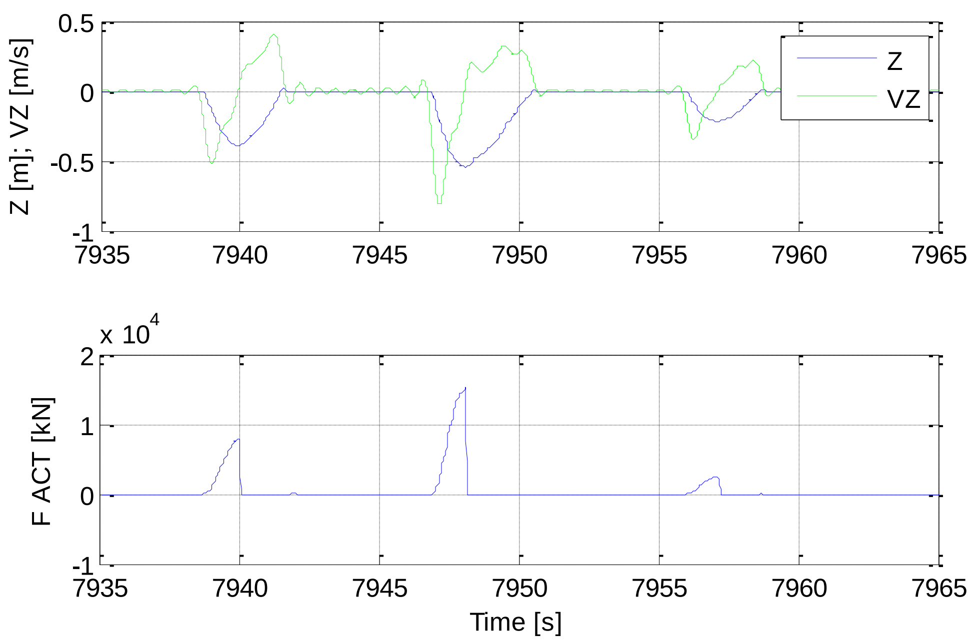

Figure 4: Typical time trace of seabed impact load cq. actuator response as represented in the hydrodynamic model tests

Real spudcan soil interaction is not characterized by a single friction coefficient. The maximum vertical reaction force varies not only with the penetration depth but also with the direction of penetration. The ratio between horizontal and vertical reaction forces (the friction coefficient) also depends on the direction in which the spudcan moves into and through the seabed. In the geotechnical models the "friction coefficient" is lower when the spudcan penetrates close to a vertical direction (90 degrees). Typical values at 60 and 45 degrees penetration direction were found to be around 0.18 and 0.26 respectively.

For the purpose of code validation against hydraulic model tests a "constant" friction factor was modeled since the tests relied on the material properties of the model spudcan and the basin floor. In the model tests the horizontal seabed friction was modeled by frictional surfaces mounted at the tip of each leg. Schematic, rounded spudcans with a diameter of 5.04 m were manufactured of HMPE 1000, as shown on Photo 2. The horizontal sliding coefficient of these spudcans was determined prior to the tests in a test bank and was also derived from the forces measured during the tests, resulting in sliding coefficients of 0.108 and 0.157 respectively.

Photo 2: leg tip with 6 DOF force measurement frame and HMPE 1000 spudcan (green)

During the model tests the jack-up was kept in position by means of a so-called soft mooring system consisting of four horizontal linear springs. The surge, sway and yaw stiffness of this system were 185 kN/m, 185 kN/m and 8.8E+5 kNm/rad respectively, resulting in natural periods for these modes of 82 s, 89 s and 42 s respectively.

The hydrodynamic model tests were performed for the following conditions:

- 1 water depth: 30m
- 1 loading condition of the jack-up: T=5.2m draft
- 2 wave directions: head on (180°) and bow quartering (150°)
- 6 seastates: H_s=2.0m, short, mid and long T_p; H_s=2.5m, short, mid and long T_p
- 4 seabed stiffnesses: K_s=10 MN/m^2, 20 MN/m^2, 50 MN/m^2, 100 MN/m^2
- 4 quasi-static clearances between the leg tips and seabed: 1.0m, 0.5m, 0.0m and -0.5m

NUMERICAL SIMULATION MODELS

The mathematical model for both codes is based on a time-step solution of the system of coupled differential equations of motion in which the fluid reaction forces are described with convolution integrals according to the Cummins' formulation, see Ref [2]. The time domain solvers use linear diffraction data, wave forces, added mass and damping. The equation of motion is integrated taking into account the own inertia, added inertia, wave loads, damping loads, hydrostatic restoring forces and leg to seabed impact loads. Frequency dependent added mass and damping coefficients are transformed into inertia coefficients, retardation functions and response functions. The equation of motion is:

$$[M_{kj} + m_{kj}(x_j)]\ddot{x}_j(t) + \int_{-\infty}^{t} K_{kj}(t-\tau)\dot{x}_j(t)d\tau + C_{kj}x_j(t) = F_j(t, x_j) \quad \text{[Eq. 2]}$$

Where:`

- $[M_{kj}]$: mass matrix
- $[m_{kj}]$: added mass matrix at infinite frequency
- $[K_{kj}]$: retardation function
- $[C_{kj}]$: global stiffness matrix
- $\{x_j\}$: displacement vector
- $\{\dot{x}_j\}$: velocity vector
- $\{\ddot{x}_j\}$: acceleration vector
- $\{F_j\}$: load vector

The load vector $\{F_j\}$ consists of:

- Wave load
- Drag loads on hull and legs
- Soil reaction on leg tips during the impacts

MARIN SIMULATION MODEL

MARIN's existing multi-body time domain simulation code aNySIM is used as the basis of the coupled geotechnical-hydrodynamic model. The multi-body time domain simulation approach is described in Ref [3]. A geotechnical module developed by Deltares, predicting the seabed reaction loads on the leg tips, is coupled to the existing time domain model to contribute to the load vector $\{F_j\}$ at the right hand side of Equation 2. The following geotechnical models are included in the geotechnical module:
1) Initial Simplified Soil Model (SSM);
2) Advanced Soil Model (ASM) based on geotechnical centrifuge tests and Anura3D simulations;
3) Artificial simplified soil model as applied in the hydrodynamic model tests, see Equation 1.

For the simulations described in the present paper the third soil model was applied to provide a one-to-one comparison with the model test results and allow validation of the numerical model against the model test results. The three lower values of the vertical seabed stiffnesses as applied in the model tests are applied, i.e. K_s = 10, 20 and 50 MN/m^2. The horizontal friction coefficient was set to 0.109.

Hydrodynamic model
The first order wave loads, added mass and potential damping on the hull of the jack-up are calculated with MARIN's frequency domain diffraction analysis program Diffrac. Drag load coefficients are applied to the hull and four cylindrical legs to result in quadratic damping. Furthermore linear and quadratic damping contributions are added to the hull to represent viscous damping effects and to match the results of free floating decay model tests.

Structural model
The jack-up is represented by a total of nine rigid bodies coupled to each other by means of stiffness and damping matrices: one body represents the hull of the jack-up, four bodies the legs and four bodies are used to represent the spudcans. High stiffness values (i.e. high rigidity) and associated damping has been applied for the coupling between these bodies.

GUSTOMSC SIMULATION MODEL

The GustoMSC leg-seabed impact analysis is performed using the in-house computer program LIMP which determines the dynamic response due to leg-to-seabed contact by means of a time domain simulation of the complete afloat jack-up. The hydro-structural model of the jack-up consists of as a mass-spring-damper system with a single mass having six degrees of freedom. The legs are modelled as simple linear beams clamped at the lower guide. Bending (EI) and axial (EA) stiffness of the leg, leg-to-hull interface and hull are taken into account.

Hydrodynamic model
The linear diffraction/radiation code WAMIT is used as potential flow frequency domain solver: the solution of the boundary-value problem provides the input to be used within LIMP, which consists of frequency-dependent wave loads, added masses and linear (radiation) damping.
Quadratic damping is then added to the model within LIMP by means of drag elements such that the motion in free floating condition (i.e. without impacts) measured during the model test is matched.

Structural model

The leg properties have been modelled and entered in the LIMP program by means of equivalent axial and bending stiffness. As shown in figure 2, the legs, as built for the model test campaign, consist of several components and some assumptions and simplifications are made in order to model their behavior by means of an equivalent beam. For the axial stiffness only the contribution of the pushing rod (moving part) is considered, whereas for the bending properties both the contribution of the outer cylinder (fixed part) and the part of moving rod sticking out from it are taken into account.

The hull and leg-to-hull interface stiffness has been set to high values (i.e. high rigidity): in this specific case the exact evaluation of these quantities is not deemed of primary importance as the whole system, consisting of hull, legs and leg-to-hull interface, has a high rigidity. However it is highlighted that sensitivity checks have been performed varying the hull and leg-to-hull interface stiffness, showing that the results are only weakly affected by these quantities.

Leg to soil behavior

Various soil models for typical offshore conditions are available within LIMP. The artificial simplified soil model as realised in the model tests is used for the numerical simulations (see equation 1).

The vertical leg-to-soil behaviour is modelled by a (static) penetration resistance curve acting as a non-linear spring. For the horizontal leg-to-soil behaviour of the leg a stick-slip model is used. At the start of contact the horizontal position of the footing is fixed and the load is determined using the bending stiffness (stick). If this load exceeds the horizontal resistance, corresponding with the actual penetration and vertical load, the horizontal load is kept at its maximum value and horizontal displacement takes place (slip). Each individual impact is treated based on virgin soil conditions.

Horizontal reactions are further split in a part for incrementing (push-in) and decrementing (pull-out) penetration: the horizontal resistance during push-in consists of a friction component based on the vertical resistance and is present if the leg is penetrating further into the soil. A horizontal friction coefficient of 0.157 is applied.

The horizontal resistance while pulling-out is set to zero as there is no vertical force delivered by the actuators and resulting horizontal reaction as soon as the leg is moving upwards.

RESULTS

Results of a selection of model tests are compared to the results of numerical simulations performed with both numerical models. An overview of the selected tests and test conditions is given in Table 2.

Test No.	Wave condition JONSWAP (γ=3.3)			Seabed condition	
	Direction [deg]	Hs [m]	Tp [s]	Clearance [m]	Ks [MN/m^2]
205003	180	2.5	8.5	1.0	10
205004	150	2.0	8.5	1.0	20
205005	150	2.5	8.5	1.0	20
305004	180	2.0	8.5	0.5	20
305006	180	2.0	8.5	0.5	50
305007	150	2.5	8.5	0.5	20
305009	150	2.0	8.5	0.5	50

Table 2: Selected model test and simulation conditions

In order to achieve a one-to-one comparison between model tests and numerical simulations the time traces of the wave elevation as realised in the basin has been provided as an input to the numerical models for each of the simulations performed.

Jack-up motion response

Power spectral density (PSD) functions of the jack-up motion response derived from the time traces of the tests and numerical simulations are presented in Figure 5 for 1.0m and 0.5m clearance between the leg tip and the seabed. The tests and simulations are performed for the exact same wave realization and seabed stiffness. The results presented in these figures show the following:

- In general a good agreement is found between the spectra derived from the model tests and the numerical simulations.
- The roll and pitch response for 0.5 m seabed clearance, and to a lower extent also the roll response for 1.0 m seabed clearance, are overestimated by the numerical simulation models compared to the results of the model tests. The difference might be due to the number of impacts and dampening effect of the impacts on the motion, in particular for roll: it is in fact more pronounced for test 305007, during which more impacts occur. Some damping present in the model tests might not be included or perfectly captured in the simulation models e.g. viscous effects on the spudcans in close proximity of the seabed.
- The motion response of the jack-up clearly reduces with decreasing seabed clearance stiffness. This is caused by the increasing number of impacts between the leg tips and the seabed resulting in more energy being absorbed by the seabed.

Based on the comparison of the PSD from the model tests and both numerical models it is concluded that the numerical models are reasonably capable to capture the overall behaviour of the unit as measured in the model tests.

Leg impact loads

Distribution functions are fitted to the tests and simulations based on the 50% highest peaks in the time traces of the impact loads on the legs. A 3-parameter Weibull fit is fitted through these peaks based on which the 3-hour Most Probable Maximum (MPM) value is derived. The MPM is a statistically more reliable value than the actual maximum value and is defined as the maximum value most likely to occur during the considered period of 3-hour.

The Most Probable Maximum (MPM) impact loads on the four legs are presented in Figure 6. The results show that the largest impact loads occur on the waveward legs. For tests/ simulations with 150° wave directions this is the starboard front leg (SBF).

The impact loads on the SBF leg, including Weibull distribution fits and MPM values, from test/ simulation condition 305007 are presented in Figure 7. For the vertical impact loads only the positive loads are analyzed, resulting from penetration of the leg into the seabed during downward movement of the leg; vertical seabed reaction forces during upward leg movements (such as suction effects) have not been represented in the model tests, nor in the present series of simulations to mimic the model test results. The horizontal impact loads are influenced by the vertical impact loads and modeled friction with the seabed. Due to the motions of the jack-up these act in positive as well as negative direction. The results presented in Figure 7 show that the horizontal impact loads are largest in negative Fx and positive Fy direction, corresponding to a load vector acting inwards onto the jack-up. The results presented in Figure 7 show a good agreement for the Weibull distribution fits and derived MPM values for the vertical impact loads.

In Figure 8 the MPM values and number of peaks in the time traces of the impact loads for negative longitudinal (Fx), positive lateral (Fy) and positive vertical (Fz) impact loads for all selected tests/ simulation conditions are presented. Lateral impact loads (Fy) for head on (180°) wave directions are not shown in this figure. In general a reasonable agreement is found between the MPM values and number of impacts from the tests and both simulation models for the vertical impact forces: the average difference between measured and calculated Fz is 8% and 12% for LIMP and aNySIM respectively. The horizontal impact loads show an acceptable agreement but the match is less good than for the vertical component: the average difference between measured and calculated Fx is 22% and 56% for LIMP and aNySIM respectively whereas for Fy these values these values are 24 and 39% respectively. It should be noted that the magnitude of the horizontal force components is highly dependent on the friction coefficient, which is set to different values in the two numerical models here considered. This can partly explain the difference in the horizontal forces between the results of the two sets of simulations.

CONCLUSIONS AND RECOMMENDATIONS

Within the Wind Jack joint industry project, geotechnical and wave basin model tests have been performed for a typical four-legged wind turbine installation jack-up platform during siting operations, with the purpose to understand and predict the leg to seabed impact loads. In the wave basin, the motion response of the jack-up and the impact loads on the legs were measured for various wave conditions, leg positions with respect to the seabed and soil stiffness.

Numerical time domain simulations have been performed using the available in-house models developed by MARIN (aNySIM) and GustoMSC (LIMP) to predict the jack-up motion behaviour and leg to seabed impact loads during siting operations. A number of model tests as performed in the wave basin have been reproduced by time domain simulations. From a comparison of the results of the model tests and the simulations, the following conclusions are drawn:

- The motion response of the jack-up platform is reasonably well represented by the numerical models, although it should be noted that the simulations slightly overpredict the roll and pitch response. Similar to the model tests, the simulations show that the motions of the jack-up are reducing due to increasing impacts with the soil.
- The maximum leg to seabed impact loads are reasonably well predicted by the numerical simulations. The average difference between simulation and model tests are in the range of 8 to 12 percent for vertical impact loads and 22 to 56 percent for horizontal impact loads.

The findings of this paper confirm that the simulation tools can be used to predict the leg to seabed impact loads and the jack-up's motion response during siting operations at a reasonable accuracy in comparison to coupled hydrodynamic-geotechnical model tests in which simplified seabed characteristics have been represented. It is considered that the simulations tools are capable to predict even more realistic motion response and impact loads on the legs as well in case more realistic geotechnical models are applied. It should be highlighted however that in reality the soil characteristics are less well defined than in the presented wave basin tests and numerical models and therefore add considerably to the overall uncertainty of the impact loads.

The following recommendations are made for further assessment and validation of impact loads on the legs of jack-up platforms during siting operations:

- Numerically assess the impact loads and jack-up's motion response with more realistic soil response models;
- Perform additional geotechnical test in sand and clay to develop more realistic soil models;
- Validate the results of the numerical models against full scale measurement results;
- Incorporate the use of state-of-the-art coupeld hydrodynamic-geotechnical time domain simulations tools in procedures to predict the impact loads on the legs of jack-up platforms.

ACKNOWLEDGEMENTS

MARIN and Deltares would like to thank the participants of the WindJack JIP for their contributions to the project: GustoMSC, HGO Infraseas Solutions, Hyundai Heavy Industries, Keppel Offshore & Marine Technology Centre, RWE Innogy, Seaway Heavy Lifting, Van Oord, Vroon, Vuyk Engineering Rotterdam.

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FIGURES

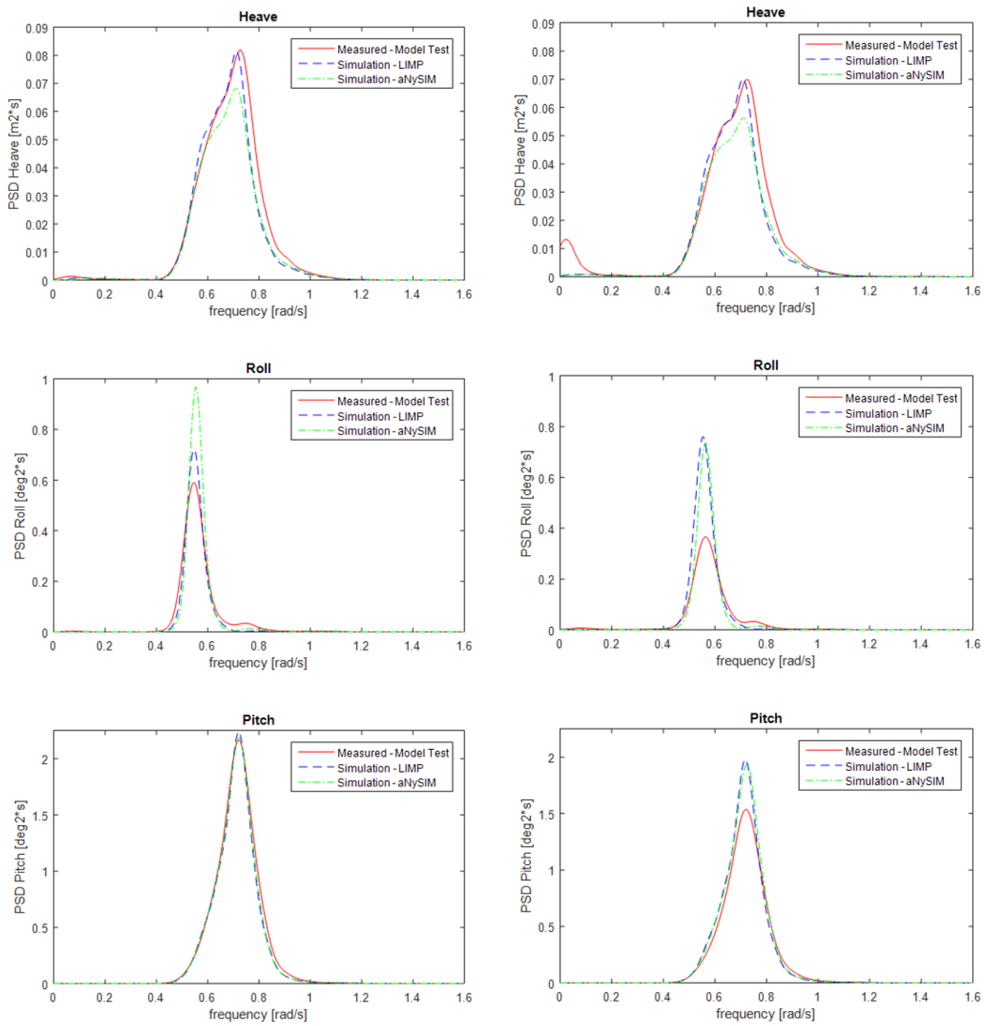

Figure 5: Power spectral density (PSD) functions from tests (red) and simulations (blue and green) for heave (top), roll (mid) and pitch (bottom) with 1.0m clearance between the leg tip and the seabed (left; Test No. 205005) and 0.5m clearance (right; Test No. 305007).

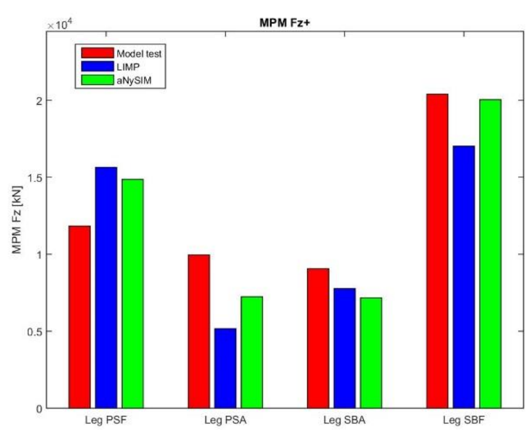

Figure 6:MPM Impact loads on the four legs from Test/ Simulation No. 305007
Leg FS (SBF) is the waveward leg for 150 deg wave condition

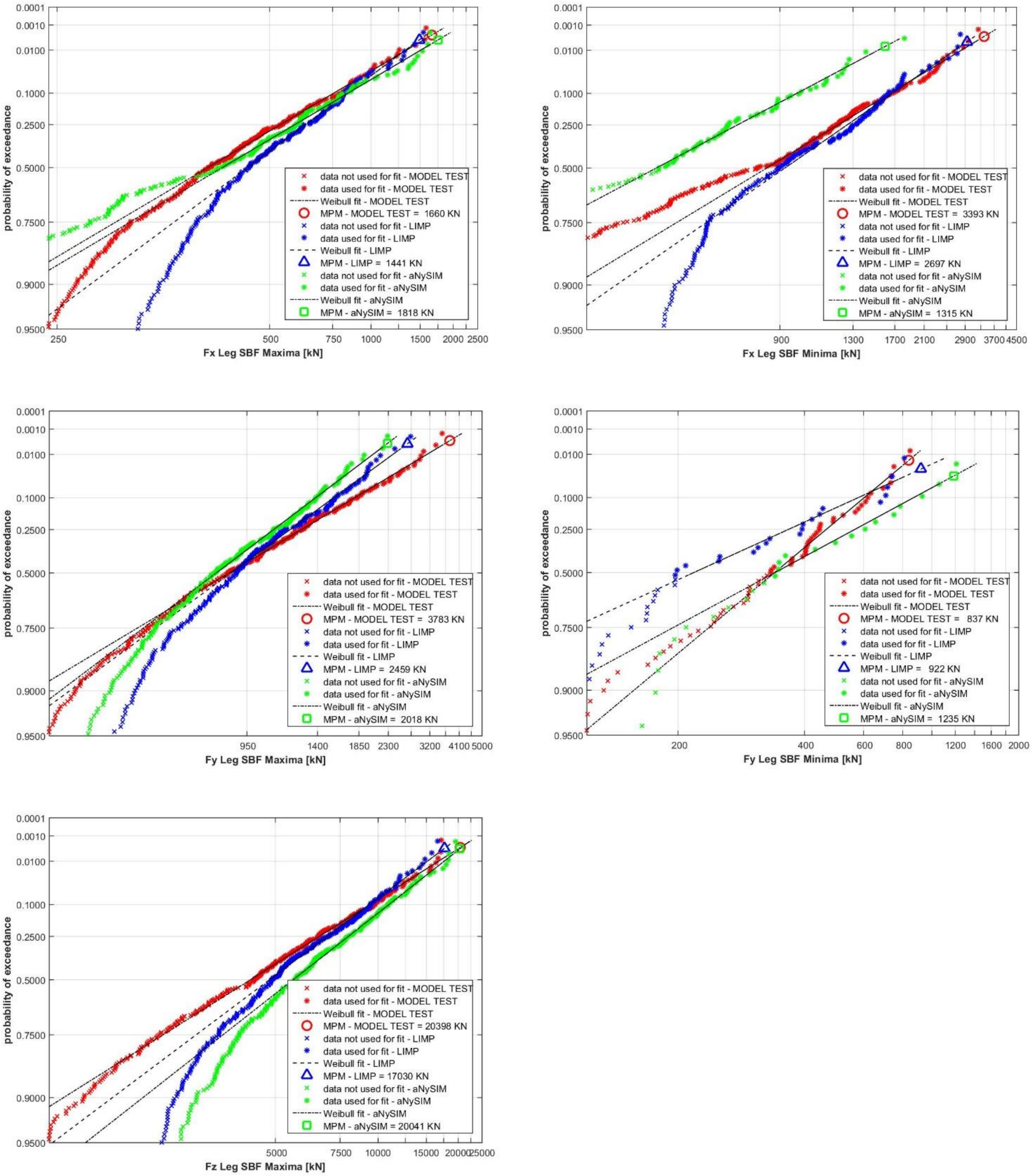

Figure 7:Weibull distribution functions of the impact peak loads on the SBF leg derived from the tests (red) and simulations (blue and green) for Fx (top), Fy (mid) and Fz (bottom) for test/ simulation condition 305007

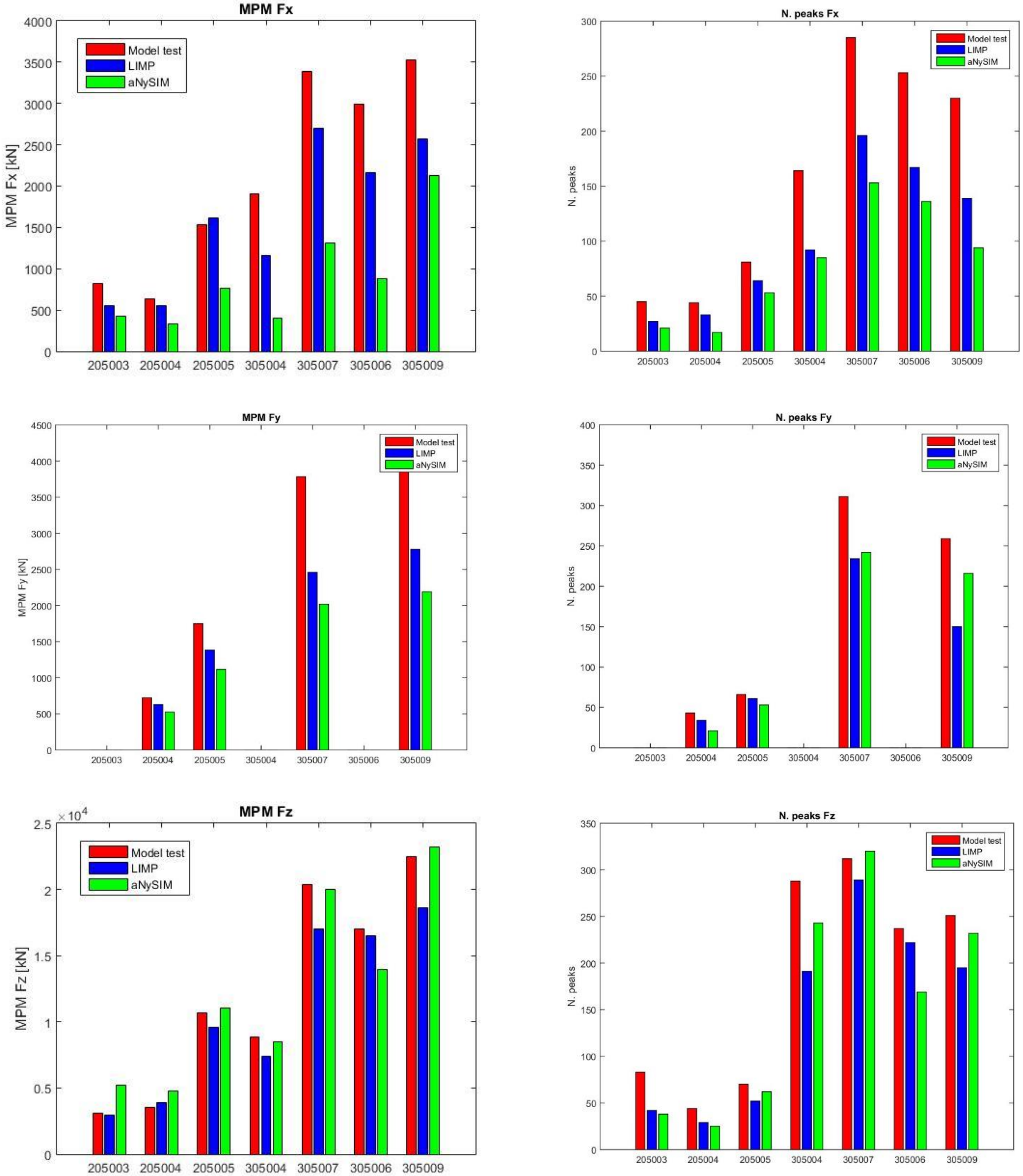

Figure 8:MPM impact loads (left side) and number of peaks in the impact time traces (right side) on the SBF leg derived from the tests (blue) and simulations (green and yellow) for Fx (top), Fy (middle) and Fz (bottom) for all selected test/ simulation conditions.