THE DROP KEEL CONCEPT: A SEMI-SUBMERSIBLE-SPAR FOUNDATION ADPATED FOR EASE OF ASSEMBLY FOR THE FLOATING OFFSHORE WIND TURBINE MARKET

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ABSTRACT

This paper provides an overview of the analysis methods, results and conclusions reached during an Innovate UK funded research program into a novel 10MW wind turbine floating foundation structure.
Current foundation designs are developments of concepts established in the offshore oil and gas sector: semi-submersible, spar and tension leg platforms. Each have their own particular technical and operational drawbacks. The project set out to develop an alternative hybrid solution to take advantage of the benefits of the semi-submersible and spar designs while removing their disadvantages. The concept considered is referred to as the Drop Keel and applied a solid ballasted keel elevated in the launch and transit conditions and deployed to depth in the operation condition. Thus, the hybrid would exhibit the semi-submersible advantages of assembly and launch at a quayside location while possessing the spar advantage of a low centre of gravity in operation.
Results from independent numerical and wave tank tests provided consistent results that proved the concept exhibited stable operating performance for the simulated offshore wind and wave conditions. However, the initial Drop Keel concept lacked commercial appeal due to a high steel and ballast weight estimate, complex assembly method, dependency on deep draft submersible barge for assembly and launch, and use of multiple mechanical lift devices that presented logistical challenges for removal during installation. Fortunately, identification of these drawbacks provided a basis for design improvement and led to a final design outcome that resolved all of these disadvantages and improved the design's commercial appeal.
keyword terms. Hybrid floating offshore wind turbine foundation, industrialisation, wave tank testing, coupled analysis

NOMENCLATURE

EDF	Electrically Driven Fan
ESS	Exteme Sea State
GUI	Graphical User Interface
H_s	Significant wave height (m)
JONSWAP	JOint North Sea WAve Project
KHL	Kelvin Hydrodynamics Laboratory
NSS	Normal Sea State
RAO	Response Amplitude Operator
SSS	Severe Sea State
T_P	Peak wave period (s)

1. INTRODUCTION

Floating offshore wind turbines appeal to energy providers seeking to meet the needs of urban coastal populations living adjacent to seabed lacking a shallow water continental shelf. Fixed bottom wind turbines are generally not economically feasible beyond 50m water depth. Regions particularly interested in this technology include California, Japan and France. The latter two have already committed investment in demonstration plants.
While demonstration plants prove that wind turbines can operate in a floating condition, design options for the structural foundation upon which the turbines float were, until recently, adaptations of either spar or semi-submersible structures used for offshore oil and gas production facilities. A semi-submersible may be defined as a floating structure with a large water plane area and a centre of gravity positioned above its centre of buoyancy whereas a spar may be defined as a floating structure with a small water plane area and a centre of gravity positioned below its centre of buoyancy. The semi-submersible relies on its water plane area and shift in centre of buoyancy to prevent its centre of mass capsizing the floating unit whereas the spar's centre of mass, being below the upthrust of the buoyancy force above, is incapable of generating an overturning moment.

Though several demonstration scale projects (less than six units) have been developed globally, the case for an industrial scale development of such concepts (batches of approximately 50 units) has yet to be proven for current foundation designs and turbine capacities (below 10MW). More recent floating foundation designs consider hybrid schemes where the foundation behaves as a semi-submersible during assembly and transportation and as a spar in operation [4] [5]. These more recent designs suspend a ballasted weight below the surface-floating structure using cables or chains. This achieves an overall lower centre of mass. The motivation for the Drop Keel concept (Figure 15) was to connect keel to surface floater via rigid tubular members. This would assure rigid connectivity between keel and surface structure, assure single body motions of the two components and increase the system's mass moment of inertia.

2 PROPOSED ASSEMBLY SEQUENCE

The Drop Keel foundation structure (Figure 15) achieves a low centre of gravity by filling the keel units with a solid, iron ore ballast. The three ballast keel units, made of interlocking concrete segments, are filled with iron ore in the form of a pumped water slurry while in port. The combined weight of the ballasted keel and the floating topside unit is such that the Drop Keel system requires assembly and launch with support of a submersible cargo barge.

In operation, each of the three floating columns suspends a ballasted keel unit with six steel tubular tendons connected to a common steel tubular ring. Each tubular ring hangs from brackets at the base of each floating column (Figure 15).

The proposed assembly sequence involves (Figure 16):

- Lay out the ballast keel concrete segments on the loadout barge;
- Place a floating column with steel tubular tendons onto each of the ballast keel units;
- Interconnect the columns with cross bracing;
- Install turbine tower and turbine assembly.
- Transport the barge to sheltered coastal location;
- Submerge barge and float off the Drop Keel assembly.

3 MOTIVATIONS FOR ANALYSIS

- Perform dynamic simulations of the Drop Keel foundation design over a range of sea states in a controlled scale model environment to demonstrate the concept's suitability as a viable proposal for a floating offshore wind foundation.
- Confirm the Drop Keel's natural response periods in heave, pitch and roll are sufficiently clear of the periods of representative waves to avoid excitation in operation.
- Determine accelerations at the nacelle for limiting turbine operational and standby sea states as a basis for discussion with suppliers as to the operability of their turbines with the proposed Drop Keel foundation design.
- Determine accelerations elsewhere in the Drop Keel structure to assist with detailed structural design.
- Compare wave tank results with numerical analysis results to assess the level of confidence that can be placed on the latter for future design assessment.

4 BASIS OF ANALYSIS

Both the wave tank model and the computer based simulations applied metocean data [1] from the Buchan Deep location, 29km east of Peterhead, Scotland, where Equinor's 30MW floating wind park is located. The water depth range is 100-140m. Figure 1 illustrates the 3 hour sea state distribution for omni-directional waves at the location. For the purpose of analysis, the sea states are classed as normal (green star), severe (yellow star) or extreme (red star).

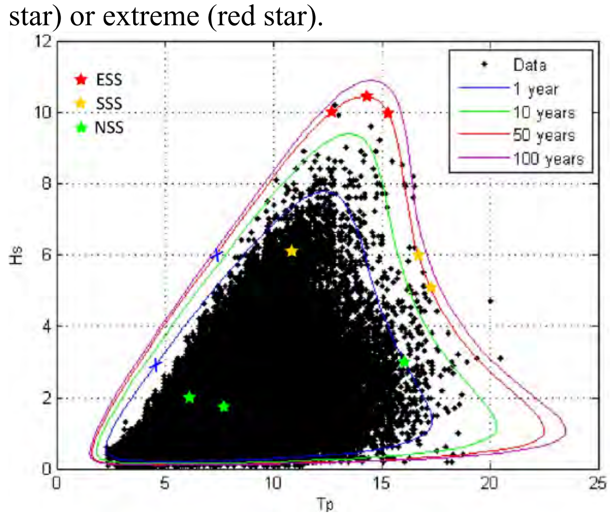

Figure 1 Buchan Deep Hs-Tp Probability Contour lines for up to 100 year return period based on omni-directional waves and 3 hour sea state.

5 SCALE MODEL TESTING

5.1 TEST FACILITY

All wave tank tests were performed at the University of Strathclyde's Kelvin Hydrodynamics Laboratory (KHL) in Scotland. The tank is 76.2m long, 4.57m wide and 2.50m deep (Figure 2). A 13.5 metre long passive type wave beach is located at the end of the tank. The reflection coefficient is typically less than 5%.

Figure 2 Kelvin Hydrodynamics Lab Test Tank

5.2 MODEL CONSTRUCTION

The geographic location and water depth of the tank facility chosen for simulation allowed a 1:50 scale. Froude scaling was used throughout. All submerged structural components were scaled exactly. A carbon fibre tube simulated the turbine tower to exactly match the model scale turbine hub height (Figure 4). Ballast weight was mounted on and moved up and down the tube to fine tune the final centre of gravity. KHL built the model and performed pendulum swing tests (Figure 3) to confirmed weight, centre of gravity and radius of gyration. The size of the model required the three components to be tested separately. Table 1 summarises the mass checks.

Table 1 Scale model key parameters compared with target values

	Mass (kg)	Kxx/Kyy (m)	VCG (m)
Full Scale	1.23E7	48.21	-0.54
Target Model Scale	98.75	0.964	-0.0108
Measured Model Scale	97.76	0.973	-0.0108
Model Difference %	-1%	0.91%	0%

Figure 3 Test model ballast keel mass properties being tested in the Pendulum Swing Device at KHL, Glasgow.

5.3 INSTRUMENTATION

Waves were calibrated prior to testing using two wave probes, one electrical and the other ultrasonic, located at the tank centre.

An electrically driven fan (EDF) was used to simulate wind turbine thrust. Based on standard 10 MW wind turbine model [2], the required maximum turbine thrust was 12N at scale (1500 kN full scale). The fan was secured rigidly in a load cell to calibrate the thrust. The standard error was 0.17N. The fan's thrust opposed the wave direction such that the thrust displaced the model in the same direction as wave propagation.

Four Qualysis cameras were used to measure the 6 degree of freedom (DOF) motion of the model. Three cameras were positioned on the ceiling, approximately 4 metres ahead of the model, and one camera placed port side (Figure 4). Qualysis system calibration was performed by waving a rod fitted with two accurately spaced markers through the measurement volume. The recorded standard deviation of the marker separation was 0.42mm.

5.4 MODEL ORIENTATION AND MOORING

Figure 4 illustrates the co-ordinate system applied to the model while in its 0° heading test position (a single column facing the incident wave front). The origin is on the still water line at the centre of the central buoyant column. All tests were performed with the model positioned at the geometric centre of the tank.

When specifying the original test requirements, a mooring arrangement had yet to be defined. Therefore a "soft" mooring arrangement was specified using elastics to maintain the model in position and minimise impact on model response.

The stiffness of such moorings is usually chosen to be as small as possible so that the characteristics of the mooring line will not affect the first-order (wave frequency) response of the model. Typically, the natural period in surge and sway introduced by the soft mooring line should be ideally at least 5 times the natural period in heave, pitch and roll.

The mooring elastics with EDF switched off (configuration A) recorded a natural surge period 18 times the natural pitch period. With the EDF on (configuration B), the moorings required additional elastics to prevent drifting outside the Qualysis measurement volume which achieved a natural period in surge 5.4 longer than the pitch natural period.

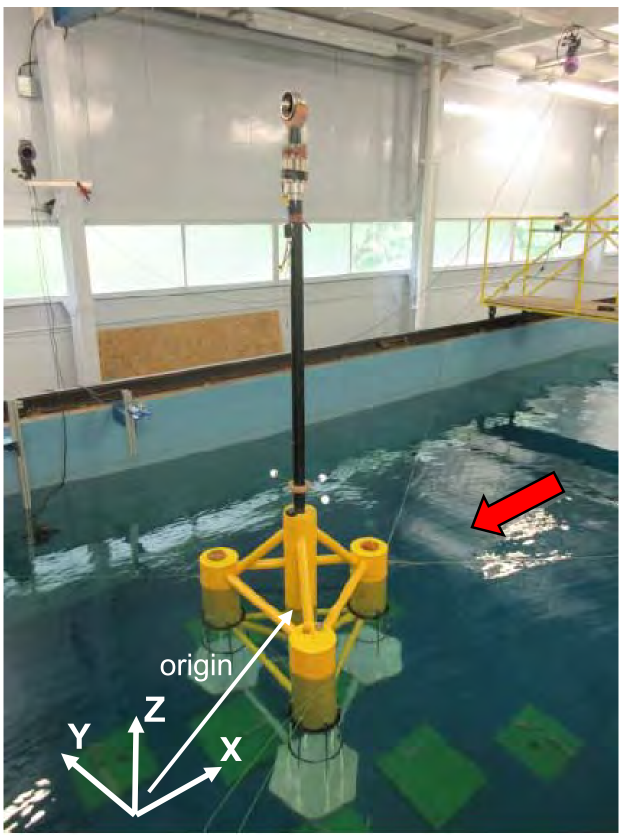

Figure 4 Scale model in test position with Qualysis cameras (top left and right corners) and soft mooring lines on water surface. Red arrow indicates direction of wave train. White arrows indicate model co-ordinate system.

5.5 FREE DECAY TESTS

Such tests determine the model's natural period in each of the six degrees of freedom (DOF) and should be clear of the expected periods of the wave spectrum of the operating location. Each test involves displacing the model in the DOF of interest. The Qualysis motion capture system records the resulting harmonic motions.

Figure 5 shows the heave response free decay curve demonstrating a typical harmonic response of decaying amplitude.

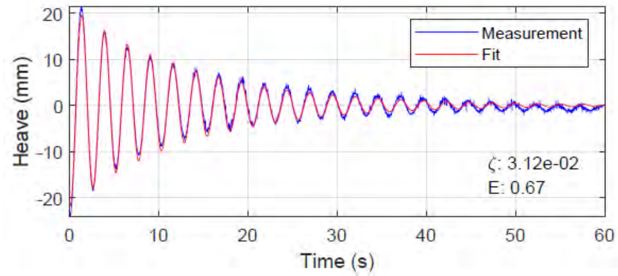

Figure 5 Linear damping fit to heave free decay test.

Further post-processing was able to determine critical damping ratio, ζ. Table 2 summarises the natural periods derived for each mooring configuration described above. Yaw motion time history proved difficult to model due to the difficulty of applying a pure yaw motion to the model. However, heave pitch and roll motions are of more interest at this stage where accurate correlation was achieved.

Table 2 natural periods for the mooring configurations considered.

	Free Decay Test Natural Period (s)		
DOF	No moorings	Config. A moorings	Config. B moorings
Heave	18.0	18.0	17.7
Pitch	32.1	32.3	30.8
Roll	32.1	32.0	--
Surge	530	566	167
Sway	1061	1018	--
yaw	495	453	--

5.6 REGULAR WAVE TESTS

A series of regular waves between 7 and 35 seconds was directed towards the model at orientation of 0° (Figure 4), 90° and 180°. The Qualysis motion capture system recorded the resulting dynamic motions and the data was processed to derive RAO plots for all 6 DOFs. Figure 6 and Figure 7 compare heave and pitch RAOs for the different wave incident angles. The results indicate:

- Correlation with the free decay tests;
- Marginal interaction of the heave natural response with the pitch natural response;

- Greater interaction of the pitch natural response with the heave natural response.

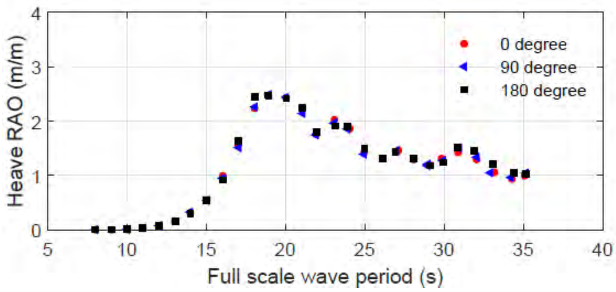

Figure 6 Heave RAO response under different wave incident angle without wind load

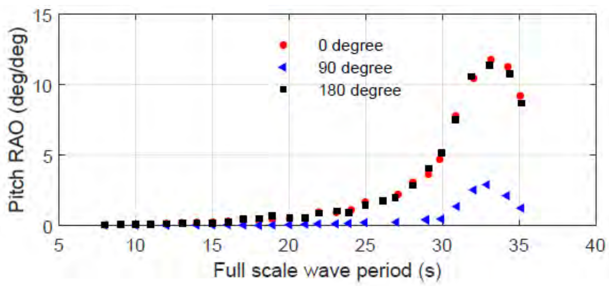

Figure 7 Pitch RAO response under different wave incident angle without wind load.

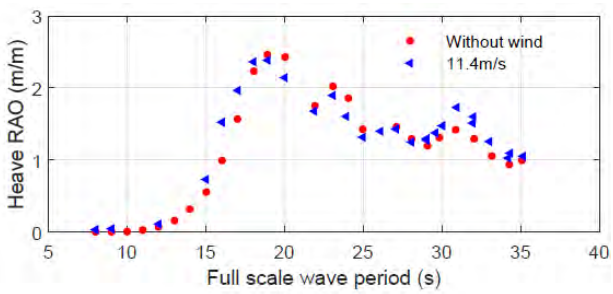

Figure 8 Comparison of heave RAO between rated wind speed and no wind

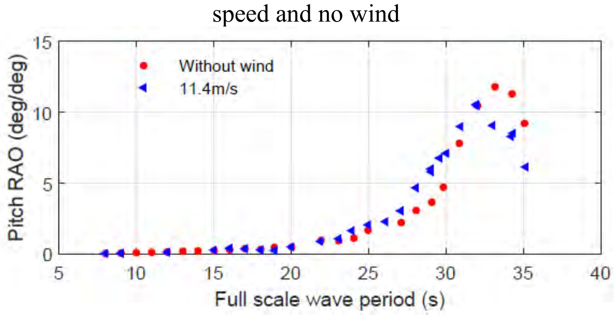

Figure 9 Comparison of Pitch RAO between rated wind speed and no wind.

The same regular wave tests were repeated with the EDF operating at a full scale thrust of 1500kN to simulate the effect of the turbine operating at its maximum power. Based on reference [2], this occurs at an ambient wind speed of 11.4 m/s. Figure 8 and Figure 9 compare the effect of turbine operation on RAO. Results suggest the inclusion of the wind load has insignificant effect on the regular wave response, particularly for wave periods smaller than 25 seconds which are more likely to be experienced in practice. Differences that do occur are likely due to the water plane area of each main vertical column becoming elliptical when inclined. This slight increase in water plane area results in a general drift of the RAO response curve towards lower wave periods.

The Qualysis system was also able to derive acceleration values at various locations on the model during regular wave tests. Figure 10 compares acceleration in the x- direction at the model's centre of gravity and nacelle with and without the applied turbine rotor thrust.

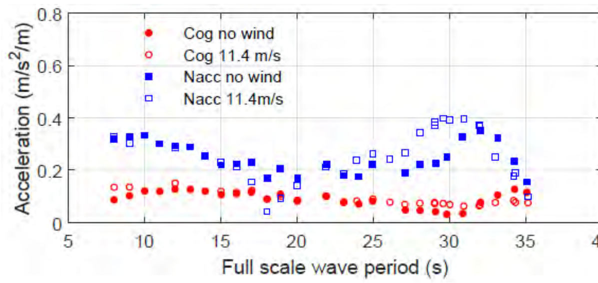

Figure 10 Comparison of derived acceleration at CoG and nacelle under wind and no wind conditions.

5.7 IRREGULAR WAVE TESTS

Ten combinations of significant wave height H_s and Peak wave period T_p were selected as representative sea states of the Buchan Deep location. Table 3 Table 3 Full Scale Sea State Parameters used for irregular wave testing.summarises these conditions in which the colour coding corresponds to the Extreme, Severe and Normal sea states referred to in Figure 1. The values in the column 'key' correspond to specific locations on the scatter diagram of Figure 1. TOC refers to specific turbine operating conditions addressed by the numerical analysis.

All sea states were run with the EDF switched off (wind speed 0 m/s) and three with EDF switched on to simulate the turbine operating in an extreme, severe and normal sea state. JONSWAP specta were used with the corresponding gamma values quoted in Table 3.

Each simulation was run for 30 minutes at scale (3.5 hours full scale). After testing, comparisons were made between each target and measured wave spectrum to confirm extent of alignment.

Figure 11 shows a representative comparison for sea state IW_03.

Table 3 Full Scale Sea State Parameters used for irregular wave testing.

Test No.	Key	Hs (m)	Tp (s)	Gamma	Wind speed (m/s)
IW_01	LC13	10.9	14.6	1.9	0 , 24
IW_02	FYL	10.0	12.7	3.1	0
IW_03	FYU	10.0	15.3	1.2	0
IW_04	FYU	5.0	17.3	1.0	0
IW_05	LC4,10	6.0	11.2	1.6	0
IW_07	FYU	6.0	16.7	1.0	0
IW_08	FYU	5.0	17.3	1.0	0 , 11.4
IW_09	LC1,16	1.9	7.7	1.0	0
IW_10	CSD	2.0	6.0	2.4	0
IW_11	OYU	3.0	16.0	1.0	0 , 11.4

LC(X): closest corresponding Table 4 condition
FYL: 50 year lower Tp
FYU: 50 year upper Tp
CDS: centre of scatter diagram
OYU: one year upper Tp

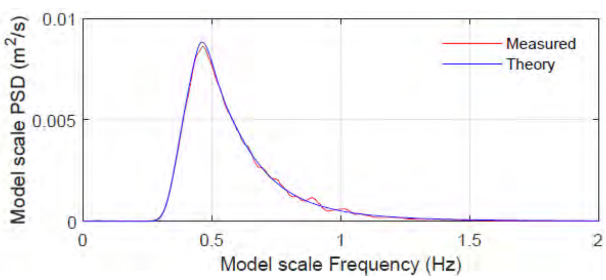

Figure 11 Comparison of power spectrum density between measured and theory seastate,IW 03: Hs=10.0 Tp=15.3

Results from the irregular wave tests were reported as a set of probability of exceedance plots of which Figure 17 and Figure 18 are representative and provide a comparison between the same sea state but with turbine operating and not operating.

5.8 GENERAL OBSERVATIONS

Results from the mooring stiffness tests also provided information about the inclination of the model under known thrust loads. Figure 12 indicates the expected incline angle at 150 kN is approximately 6.5°.

During the more severe wave conditions, water was passing over the main decks of the outer columns of the model. This suggested that an increase in freeboard height may be required though this was undesirable from a production aspect as it would require an increase in structural weight and also result in a centre of mass increase. It was this concern that in part motivated the change of design described in section 7.

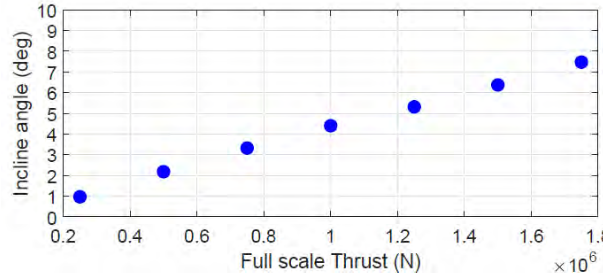

Figure 12 Inclining angle under turbine thrust load

6 NUMERICAL MODELLING

A computer based simulation of the Drop Keel foundation structure was performed using DNV's SESAM software suite, applying the same parameters used for the scale model wave tank tests.

6.1 BASIS OF THE NUMERICAL MODEL

SESAM's WADAM module simulated hydrodynamic loads, covering added mass, radiation damping, hydrostatic stiffness, Froude-Krylov and diffraction forces and mean drift forces.

The SIMA module was used to prepare a fully coupled, aero-hydro-servo-elastic dynamic response in time domain. SIMA acts essentially as a GUI so the user can set parameters for the more dedicated analysis modules within SESAM.

The co-ordinate system applied is shown in Figure 13. Note that this is 90° out of phase relative to the wave tank test model such that roll in one system is pitch in the other.

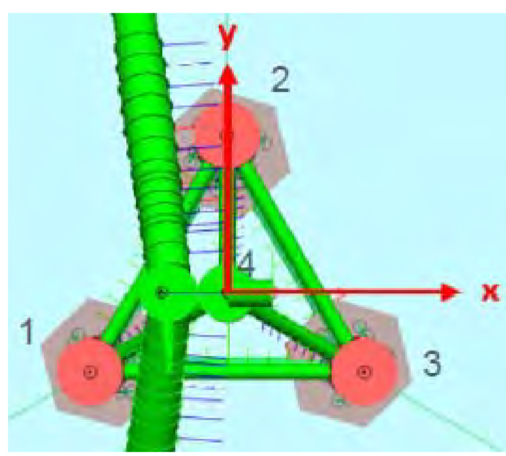

Figure 13 Frame of reference for the WADAM and SIMA models

A mesh density of 1m x 1m was used for the WADAM model which consisted of 8527 diffracting panels and 7310 Morison elements (Figure 14).

Similar to the wave tank tests, the numerical analysis simulated free decay tests, regular wave tests and irregular seas states. Regular waves of period 4 to 38 seconds at 0.5 second intervals were applied to the model across the same angular arc (0° to 180°) but at 15° rather than 90° intervals.

Irregular waves considered the more critical normal, severe and extreme seas states listed in Table 4 and defined by [3]. Each set of 3 load cases considered wind, wave and turbine rotor all aligned and at headings of 0°, 30° and 60° relative to the fixed foundation co-ordinate system (Figure 13).

Table 4 Load cases for numerical coupled analysis

Load case ID	Design load case [4]	Description
1 to 3	1.2	Normal Operating Condition
4 to 6	1.6	Severe Sea State at Rated Wind Speed
10 to 12	5.1	Emergency Shut Down
13 to 15	6.1	Idling 50-year Storm
16 to 18	7.2	Idling Normal Sea State

6.2 RAO RESULTS

Figure 19 and Figure 20 show WADAM's heave and roll RAO plots respectively with the wave tank test results shown as a dashed red line. Due to the co-ordinate system differences, Figure 20 shows the wave tank pitch curve for comparison. Table 5 compares natural periods derived physically and numerically. The shorter periods derived from the numerical analysis reflect the additional stiffness of the actual mooring system simulated in the computational model compared with the soft mooring system used with the physical model. The physical model also identified interaction between the natural periods which the computational model did not. The computational model also shows sensitivity to coefficient values such as drag, damping, stiffness and added mass and, to an extent, results from the wave tank test were used to fine tune the numerical model. Therefore, the results demonstrate the value of wave test data for a more in depth understanding of dynamic behaviour.

Table 5 Comparison of Natural Periods determined by physical and numerical modelling

DOF	Natural period derived:	
	by wave tank	numerically
Heave	18.0	18.0
Roll	32.0	30.5
Pitch	32.4	30.5

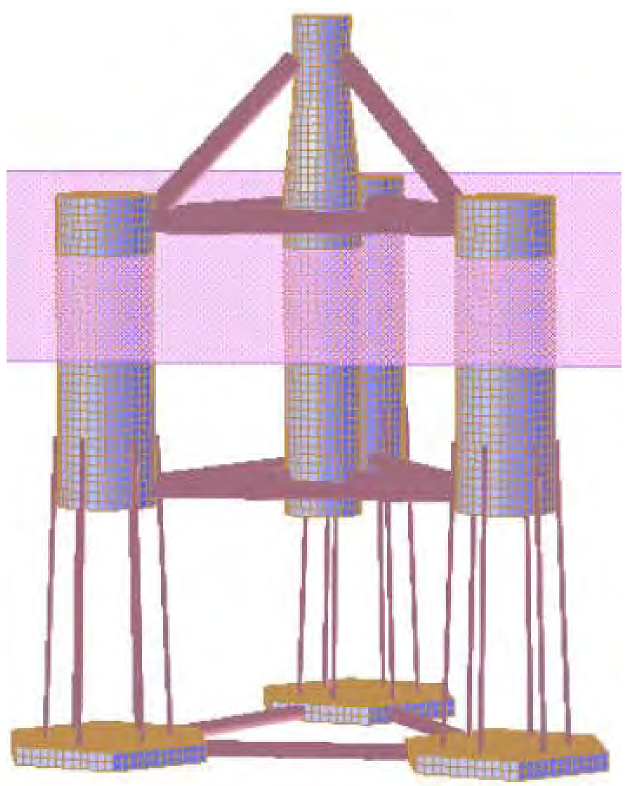

Figure 14 The 3D panel and Morison model used for hydrodynamic analysis in WADAM

6.3 IRREGULAR WAVE RESULTS

Table 6 summarises the load cases that produced maximum values. The results indicate the Drop Keel model is generally “soft laterally” and “stiff vertically”.

The Drop Keel foundation motions were generally greatest in the Normal and Severe Sea State, driven primarily by wind load. At future design stages, the turbine controller may be tuned to control the platform surge/sway and pitch/roll motion as required.

Table 6 Maximum motions and loads from irregular sea state simulations in SIMA

motion / load	case ID	value
pitch	LC 4	9.5°
	LC 1	9.3°
heave	LC13-15	4.9m
surge	LC1, LC4, LC10, LC13	44-49m
Mooring line tension	LC13-LC15	4080kN

7 DESIGN FOR ASSEMBLY, LAUNCH & INSTALLATION

Of critical importance to the Drop Keel concept was ease and cost of fabrication. Issues arose during the project that suggested the original concept would not be commercially attractive.

The proposed assembly sequence outlined in section 2 was discussed with an established fabrication company engaged in fixed bottom wind turbine foundation structure assembly. They raised concerns regarding the proposal to assemble modules on critical path. They advised that the upper floating module and each of the three ballast units be assembled off critical path. The weights of these four larger units would challenge available crane capacity. Integration of the multiple steel tubular tendons between the upper floating unit and the three separate keel modules would raise challenges for fit up tolerances.

As analysis progressed, there were concerns for the ability to assure rigid fixity between the ballast keel modules and the floating foundation unit using the proposed hang off arrangement between tubular ring and hang off clamps. A more assured rigid connection between the two was required.

The addition of solid ballast weight to the structure prior to load out added a very large weight and draft penalty to the structure that placed a great constraint on potential assembly barge availability.

Vertical, linear deployment of the ballast keel units required mechanical handling devices demanding power source on board and removal of the whole handling system after installation. The ability to retract the keel unit at some point in the future would require re-installation of the handling system.

FESL conducted several design reviews and identified key improvements to reduce weight and complexity of assembly and operation:

- standardise materials: replace the multi-unit concrete design of the keel module with a steel tubular design built as a single unit off the critical assembly path.
- reduce components: replace three separate keel modules with one single unit.
- simplify the moving parts: hinge the ballast keel modules about the base of the upper floating unit and deploy them to depth using a rotation action controlled by ballast water. This also enables the ballast keel to be deployed deeper and simplifies the recovery operation.

As a result, with a deeper deployed keel unit, there was a reduced dependency on water plane area for stability to the extent that the upper floating module could be completely submerged. The improved stability, reduced number of components and removal of the need to maintain freeboard resulted in a two-thirds reduction in the height of the upper floating unit main columns. The concern of wet-deck conditions in extreme sea states was removed. The design assumed a full spar configuration.

8 CURRENT WORK

Work on the original Drop Keel concept presented here is complete. Results and lessons learnt are being adapted for a new phase of wave tank testing and numerical modelling on a floating wind turbine foundation concept shaped by the design improvements of section 7.

9 CONCLUSIONS

The tank tests and numerical modelling presented demonstrate that the original Drop Keel Concept can provide an acceptable foundation for a floating offshore wind turbine. However, the original design and assembly proposals described presented hurdles to industrialisation and ease of installation.

Significant weight reduction and installation improvements were achieved during the research program through observation of the wave tank experiments, review of the analysis results and discussions with those engaged in delivery of similar manufactured units.

The most significant design improvement was to lower the keel centre of mass to allow the upper floatation unit to be completely submerged and become a full spar design with minimal water plane area.

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Figure 15 Isometric view of drop keel foundation concept in operational configuration

Figure 16 Isometric view of drop keel foundation concept in assembly/transit configuration

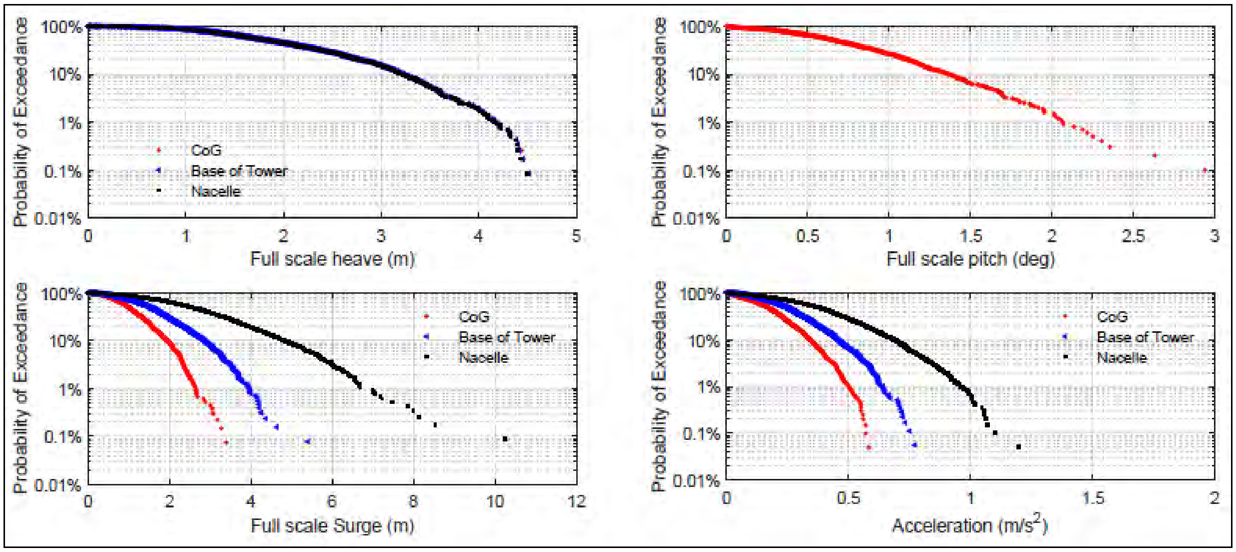


Figure 17 Exceedance probability for heave, pitch, surge and acceleration. Seastate: SSS IW 008, Hs: 5.0m Tp:17.3s,wind speed: 0 m/s

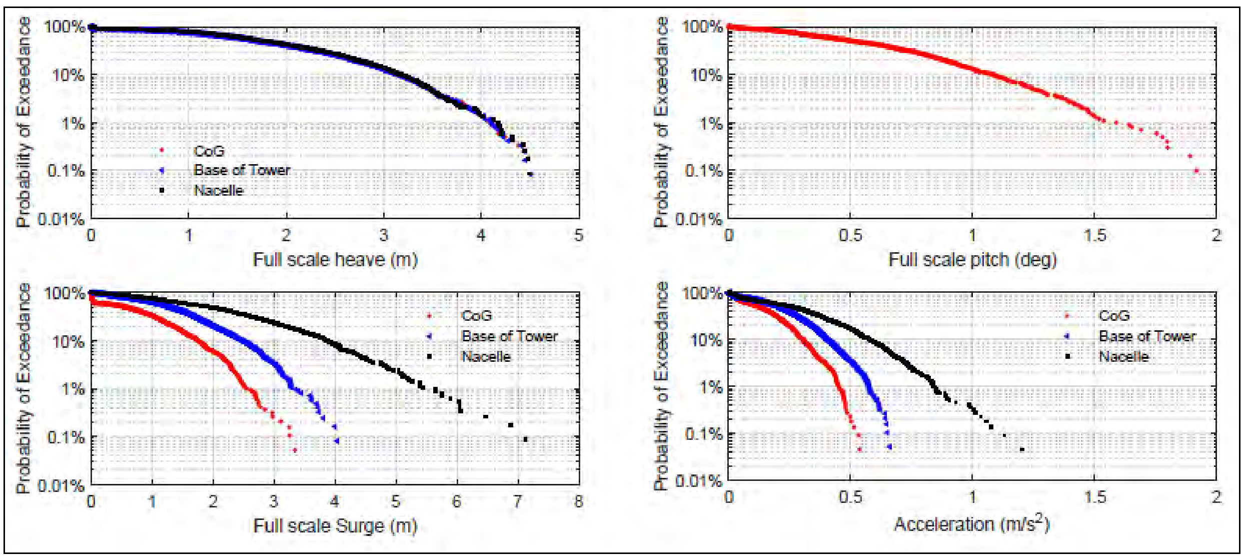
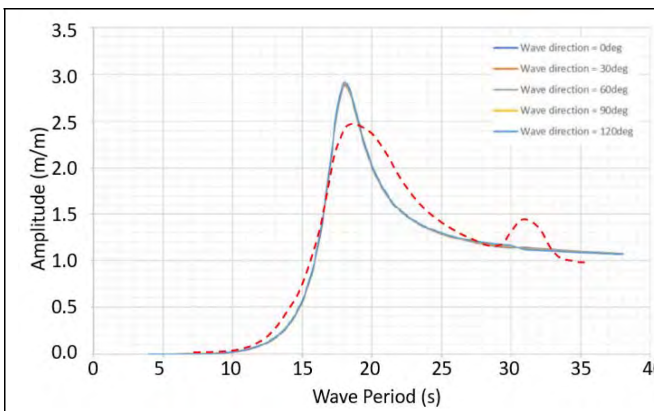
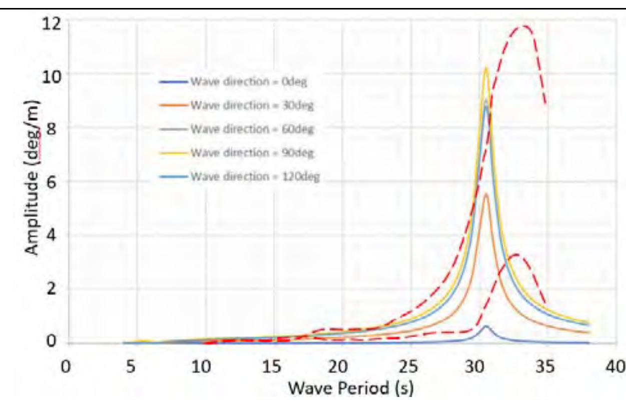


Figure 18 Exceedance probability for heave, pitch, surge and acceleration. Seastate: SSS IW 008, Hs: 5.0m Tp:17.3s,wind speed: 11.4 m/s





Dashed line indicates equivalent wave tank generated values.

Figure 19 WADAM derived RAOs in heave

Figure 20 WADAM derived RAOs in roll