Wave-Current Blockage:
Reduced Loads and Structural Responses of Lattice-Legged Jack-ups

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Abstract

We summarise research work on the estimation of extreme loads from waves and current on space-frame offshore structures. Whilst relevant to both new builds and the re-assessment of old and ageing offshore platforms, our results are likely to be equally important for the estimation of extreme motion of dynamically sensitive structures such as jack-ups. Current blockage is a field effect. Due to the presence of the rest of the structure, the flow velocity on each structural member is reduced on average, leading to smaller overall loads. The first 'current blockage' model was proposed by Taylor [1991, OTC6519], and incorporated into standard industry practice (API, DNV and ISO). This is a simple improvement to the original Morison equation which predicts forces using the undisturbed open ocean flow properties. More recent work shows that unsteady large waves on top of a steady current introduces additional blockage, described here as wave-current blockage. A Computational Fluid Dynamics (CFD) model for a porous block is used as a global representation of the structure with embedded Morison drag and inertia stresses distributed over the enclosed volume of the space-frame, see Santo et al. [2015 Computers & Fluids 115, 256–269]. At a member scale, the standard Morison equation is used, but on the local flow. This local flow speed is reduced because of overall interaction between the structural members interpreted as resulting from a distributed array of obstacles. The effect of structural response motion on the hydrodynamic forces can be accounted for using the Morison relative velocity form, and this is equivalent to substantially increasing the fluid damping. Since the Morison equation is semi-empirical, drag and inertia coefficients are still required, consistent with present industry practice.

Introduction

The Morison equation [4] has been used for many years to estimate fluid loading on a single column and by simple summation the total load on a lattice or space-frame structure. This splits the loading into drag and inertia components. The drag component is a viscous effect with the structure of the wake being important. In contrast, the inertia is essentially a potential flow effect, being related to the local increase in kinetic energy of the fluid as it is locally accelerated around the body. Both the drag and inertia contributions are modelled with empirical coefficients C_d and C_m. The Morison equation has served the offshore industry well over almost 70 years.

When considering loading on lattice structures under storm conditions, it is necessary to include the contributions to the local flow from both waves and in-line current. The current may have a tidal contribution as well as that driven by the storm. Obviously the current is a mean flow whereas the local wave kinematics are (mostly) oscillatory. In early work on 'current blockage' [13, 14] first presented at OTC in 1991, analysis based on simple actuator disc theory showed that the mean force arising from a steady flow through an array of relatively closely spaced columns was smaller than the sum of the forces on each of the columns in the same approach flow neglecting any interaction effects. The results of this analysis have been incorporated in the API and SNAME standards [1,12] as simple current reduction factors, with the interaction effect leading to the actual current within the volume of the lattice being typically 70-80% of the undisturbed far-field value. The effective current within the structure, u_B, is lower than the approaching undisturbed current, u_C, by a factor containing the net hydrodynamic area, $C_D\, A$, and the frontal (projected) area of the entire lattice structure, A_F, which is expressed as:

$$u_B = u_C \frac{1}{1 + \frac{C_D\, A}{4\, A_F}}$$

Since this result was published, we have made further developments on the analytical model of wave-current blockage for regular waves and steady current, and most recently for wave-current-structure blockage, as documented in [10, 11, 14]. Although convenient for comparison to experimental data, these analytical models require approximations beyond what is needed for CFD, so are not really suitable for practical industrial applications.

This paper summarises our investigations of the fluid loading of lattice-type structures in extreme waves and current. Further details are available in a series of published journal papers [5-11 and 14] and the initial OTC paper [13].

CFD-based approach

We propose that the actual space-frame or lattice structure be replaced as far as general fluid loading calculations are concerned by a porous block or blocks. We assume that the actual structure can be replaced by distributed stress elements according to the local Morison equation, local in the context of disturbed flow kinematics being used within each computational cell. The standard Navier-Stokes equations are modified to:

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot [\rho \mathbf{u}\mathbf{u}^T] = -\nabla p^* + \nabla \cdot [\mu \nabla \mathbf{u} + \rho \boldsymbol{\tau}] - \mathbf{S}$$

The new stress $\mathbf{S}$ represents the net effects of the drag and inertia components in the Morison equation, here averaged out over the enclosed volume of the lattice structure:

$$\mathbf{S} = \frac{1}{2} \rho F \mathbf{u}|\mathbf{u}| + C_m' \frac{\partial \rho \mathbf{u}}{\partial t}$$

The Morison quadratic resistance is replaced by a Forchheimer stress-type coefficient $F = C_d\, A/(A_f\, L)$ used, with L as the downstream length of the flow cell, to represent quadratic resistance for flow through porous media. The Morison inertia contribution is retained, now being a volume average over the cell. In our analysis so far, we have assumed that the hydrodynamic loading is uniform all over the enclosed volume of the structure for convenience but this isn't necessary. For example, marine growth on a real structure could be accounted for by simply increasing $C_d\,A$ close to mean-sea-level to account for both the increased roughness and the increase in effective member diameter. Of course neither is necessary when simulating our laboratory tests, which are described next.

Thus, the CFD calculation automatically accounts for all large-scale blockage effects around and within the structure. This is in sharp contrast to the standard Morison approach which uses the undisturbed (free-stream) flow kinematics. This approach has been implemented using CFD in the open-source software OpenFOAM and waves2foam [5, 6, and 7]. Figure 1 shows a numerical wave tank containing a porous block representation of a lattice structure. The waves and the current enter at the left of the figure, the structure is roughly one third of the way along the tank, and the waves are artificially damped at the right hand side to prevent reflection back upstream.

The only change to the CFD needed to account for structural motion is to incorporate the relative velocity form of the Morison drag into the Forchheimer term,

$$\mathbf{S} = \frac{1}{2}\rho F(\mathbf{u} - \mathbf{u}_s)|\mathbf{u} - \mathbf{u}_s| + C_m' \frac{\partial \rho \mathbf{u}}{\partial t}$$

where $\mathrm{u_S} = \dot{\mathrm{x}(\mathrm{t})}$ is the velocity of the structure relative to ground [2, 3, 9]. We make one approximation: we simplify the numerical implementation by not moving the porous block through the fixed mesh. We simply include the imposed stresses distributed over the original position of the structure, and the actual motion of the structure is solved for outside the CFD calculation.

Validation of hydrodynamic loads and structural displacements at large laboratory scale

A 1:80 scale lattice structure model was tested in a large towing and wave tank in the Kelvin Hydrodynamics Laboratory of University of Strathclyde in two sets of tests in 2016 and in 2017, see Figures 2 and 3. The model was suspended below the carriage which runs along the tank to provide a uniform current. Waves are produced with a set of EDL wavemakers and a wave absorbing beach is installed at the other end of the tank to suppress wave reflection. The aim of the Kelvin Lab tests was to provide validation of the proposed numerical fluid loading approach.

The lattice structure is modelled after a typical second-generation 4-legged North Sea platform operating in 115 m water depth, see Figure 2. In the experiments the model is suspended below a carriage, which is then moved along the tank at constant speed to simulate uniform current. The model is then subjected to a range of isolated wave groups made to focus at the jacket position (as representative of extreme storm waves), and wave groups embedded in smaller regular wave backgrounds, all with different in-line current speeds. With a length-scale ratio from the lab to the field of $80\,\times$, this also applied to the wave height and structural displacements. The wave kinematic and current speeds scale as $\sqrt{80}$, and the applied loads and base-shear reactions scale as $80^3 \sim 0.5 \times 10^6$, assuming the same Morison coefficients were used. Thus, the 35 cm peak wave height and a current speed of 0.14 m/s in the lab (and shown in Figure 5) are roughly equivalent at field scale to a 28 m wave height and a uniform in-line current of 1.25 m/s.

The lattice model was supported by a double pendulum arrangement from above, with vertical loads taken upwards through the pendulum and the total in-line horizontal load through a (very stiff) force transducer. The global base-shear load in waves and current was measured, both with a very stiff support (static response) and also with the structure allowed to move on springs (dynamic response). In the second set of tests springs were inserted between the model and the force transducer. Hence both the equivalent of dynamic base shear (foundation reaction) and the structural dynamic displacements were measured. Typical results are shown in Figure 5.

During the first series of tests, the jacket model was supported rigidly from the carriage and the global horizontal hydrodynamic force - time histories were recorded through the force transducer. In each case, the water surface elevation - time histories next to the model was also recorded. A porous block as a proxy to the actual lattice model was set up numerically, and the same incident wave conditions were simulated in a numerical wave tank using OpenFOAM. The numerical predictions on the total force – time histories compare well with the measurements for all range of cases with a single pair of Morison coefficients, C_d = 1.3 and C_m = 2.0, without any observed KC number effects so long as the steady current is present [8]. We also note that the drag coefficient C_d = 1.3 is consistent with simple current blockage for tow tests without waves in the tank.

The success of the first series of tests served as strong motivation for us to explore the modelling of dynamically-responding structures. In 2017, the jacket model was re-installed in the wave tank but now supported with a set of springs at both support ends to allow for free vibration, see Figure 4. The focus was to explore the excitation of a high frequency vibration modes relative to the wave natural frequency. So these tests should be relevant to the second mode of compliant towers, and the first mode of both a deep-water dynamically sensitive jacket and also jack-ups in intermediate water depth. The ratio of the resonant frequency of the structure on the springs to the peak of the input wave spectrum ($f_p = 1/T_p$) for the results shown in Figure 5 was 2.4x, with the linear stiffness of the springs and the mass of the lattice structure and pendulum components chosen such that the scaled displacements are appropriate for an intermediate depth lattice jacket and topsides in the central North Sea, say.

It should be noted that experimentally the model horizontal displacement is uniform with depth, due to the double pendulum support from the carriage in the towing tank. The global force – time history through the springs (or, equivalently, the force to the ground) was measured with a force transducer connected to one end of the supports. Because the measured forces are through the springs, the actual applied hydrodynamic forces on the jacket are inferred using a linear transfer function derived from the equation of motion of a single DOF oscillator. As well as free surface elevations, the model displacement – time histories were also recorded. The lattice model was subjected to the same set of incident wavefields and currents as previously in the 1st series of tests.

For the comparison with the dynamic tests, a porous block with distributed stresses according to the local Morison equation in the relative-velocity form is now used. The degree of agreement of the CFD results with the measurements is very encouraging, in all cases with current and using the same sets of C_d and C_m coefficients as before, see Figure 5. Most importantly, we observe considerable additional damping arising from the Morison relative-velocity contribution. This extra damping beyond what was observed in a push-test in still water is of the order 8% of critical damping. This is significantly larger than the normally assumed values of 2-3% of critical damping, as recommended by API for instance, and also much larger than the 1% of critical damping observed in separate push-tests on our spring-restrained model in otherwise still water. This additional damping can be viewed as arising from a considerably reduced fluid force, a realisation of wave-current-structure blockage effects. More detailed analysis is reported in [9].

CFD simulations including the structural motion of a lattice structure

Two methods have been implemented to obtain the numerical force predictions. The more sophisticated method requires coupling the CFD code with a second time-domain structural solver to provide feedback from the structural dynamics to the fluid dynamics. In terms of practical applications this implies full coupling (with two-way transfer of information) between the time-marching solvers in both OpenFOAM and the structural code, not impossible but this would be quite challenging to achieve efficiently for a real structure. Simulations of our experiments are more straightforward as the structural model is a simple time-marched 2nd order ODE which can be user-defined as a callable routine within OpenFOAM.

A much better practical approach is an approximation which allows an expansion of the Morison relative-velocity form (hence a de-coupling), as given by Haritos [2] and Merz et al. [3]. The approximation works well so long as the structural velocity is smaller than the disturbed (wave + current) flow kinematics, which should hold for all the practical structural vibration modes of interest. Both methods agree very well for all the cases we tested, and with the experiments.

The second method allows us to separate the CFD OpenFOAM run from the structural analysis, so there is no requirement to simultaneously run both codes. The results from OpenFOAM run for an infinitely rigid structure can be simply extracted in a convenient form and stored. This provides all the information that is required for estimating the change in fluid loading due to the structural motion. This pre-computed hydrodynamic information would then be imported into the structural code to perform full dynamic structural analysis using realistic time-varying hydrodynamic forces. Thus, it is this second method that we recommend should be developed for practical industrial applications.

The relative velocity of the Morison drag term is:

$$F_D = \frac{1}{2}\rho C_D A (u-\dot{x})|u-\dot{x}| \approx \frac{1}{2}\rho C_D A (u|u| - 2|u|u\dot{x})$$
$$= \frac{1}{2}\rho C_D A\, u|u| - \rho C_D A|u|\dot{x}$$

The first of the two terms in this approximate form is clearly the drag on the structure when fixed. The second term is a fluid-type local damping, linear in the structural velocity but also linear in the local fluid speed (not velocity, note the $|u|$).

Thus, for a good approximation to the fluid loading on a dynamically responding structure, both the standard Morison drag on the fixed structure $\frac{1}{2}\rho C_D A\, u|u|$ and the local fluid damping force coefficient $C_D A|u|$ need to be stored as output from the CFD simulation. Figure 6 shows a comparison of the measured behaviour in the Kelvin Lab, the results from fully coupled CFD and structural modelling, and the results from the splitting approximation of the Morison drag followed by a de-coupled structural simulation. The fully coupled and splitting approximation results are almost identical, and both reproduce the experimental behaviour of the 1-DOF structural system well.

With the splitting methodology giving time dependent loads on the stationary structure and the local damping coefficient pre-computed, then a full time-dependent analysis of any lattice structure could be performed. This could be either linear or full-nonlinear with the simulation of structural yield, buckling, foundation failure etc. up to complete structural collapse.

Application of wave-current-structure blockage to jack-ups

Although the lattice structure tested in the Kelvin Lab and simulated in OpenFOAM is a 1:80 simplified model of a typical second generation central North Sea structure, the results obtained are also directly relevant to the hydrodynamic loading on jack-up legs. These have close to uniform properties over the depth, at least before marine growth is accounted for, so would be straightforward to model with a CFD code like OpenFOAM. While there will be substantial blockage within each leg, whether there is any significant leg-leg interactions remains unknown. In general for arbitrary wave approach directions, the wakes of the legs would be likely ‘miss’ each other, so any leg-leg effects are probably small.

The SNAME standard for jack-ups [12] allows damping of the dynamic response to be assumed as 8% of critical damping, split into 2% from the structure, 3% from the foundation and 3% from the hydrodynamics. Our work suggest that the damping from the hydrodynamics is more likely to be of the order of 7%, giving a total damping of perhaps 12%.

In addition, even if the jack-up is assumed rigid, the fluid loading due to extreme wave and in-line current is likely to be lower than presently modelled using ‘simple current blockage’ of the current and undisturbed wave kinematics, as allowed by SNAME [12] and API [1]. Previous results on the jacket model [8] indicate that the actual peak load is of the order of 30% lower than that predicted using the SNAME and API guidance.

However, this factor is sensitive to details of the structure and the combination of wave and current, so further CFD calculations for specific example structures are justified in the same way as detailed structural modelling has to be structure specific.

Conclusions

'Simple current blockage' as included in the API and SNAME rules is still overly conservative for extreme wave and in-line current loads. There is additional wave-current interaction with the lattice structure which leads to predictions of lower peak loads. But this additional interaction is structure specific so assessing this over-prediction requires the use of a numerical wave tank in a computational fluid dynamics code such as OpenFOAM. In such a scheme, the lattice structure is replaced by a porous block with Morison-type characteristics and the required waves and in-line current can be generated.

If the lattice structure is dynamically sensitive then there is an additional wave-current-structure interaction arising from the Morison relative velocity form for the drag. This can be interpreted as enhanced structural damping as this additional force component is proportional to the velocity of the structure and retards the motion but it is driven by the fluid loading process.

Direct implementation of the Morison relative velocity form in modelling would require full coupling of the CFD and structural codes with two-way passing of information. However, the analyses can be de-coupled if the structural velocity is much smaller than the flow velocity, as will always be the case in practice. Then, the numerical wave tank can be run for the structure assumed rigid and all the necessary information for the structural analysis are extracted and stored. A fully detailed structural analysis can then be undertaken with appropriate time-varying loading.

The extensive analyses summarised here are fully consistent with the results of large-scale wave tank testing in the Kelvin Hydrodynamics Laboratory.

Although there is still much to do to translate the validated models reported here into engineering practice for a variety of space-frame types including jack-ups, we believe that this fluid loading/blockage work is a significant contribution to the hydrodynamic loading of offshore space-frame structures of lattice form.

Figures

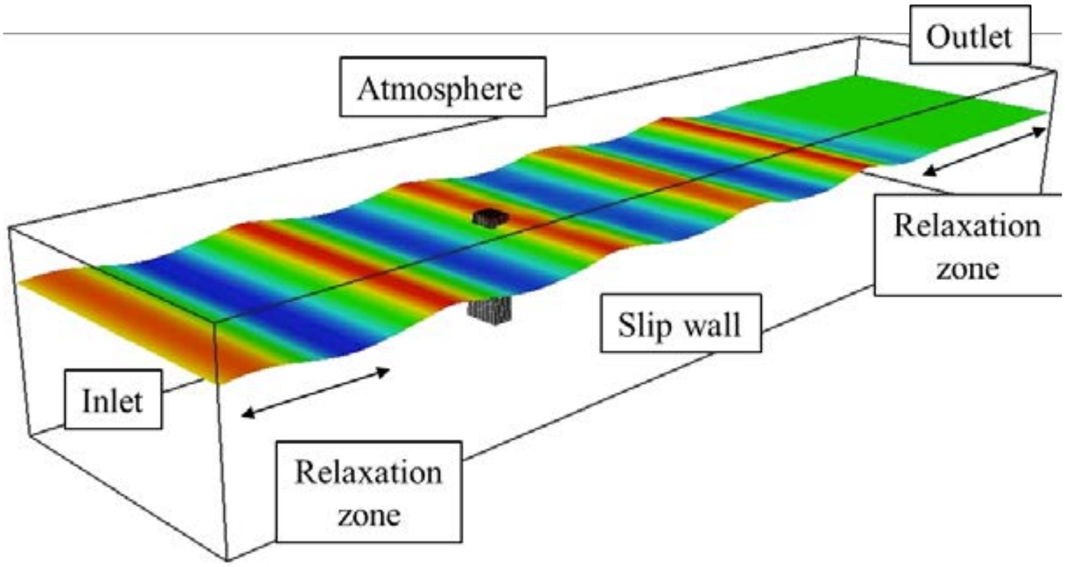

Figure 1: Layout of the computational domain. The location of a porous tower is indicated as black block. A regular wave is shown propagating from the inlet to the outlet. Red colour represents wave crests, blue represents wave troughs, and green represents water surface close to mean sea level. Also shown are the boundary conditions of the tank.

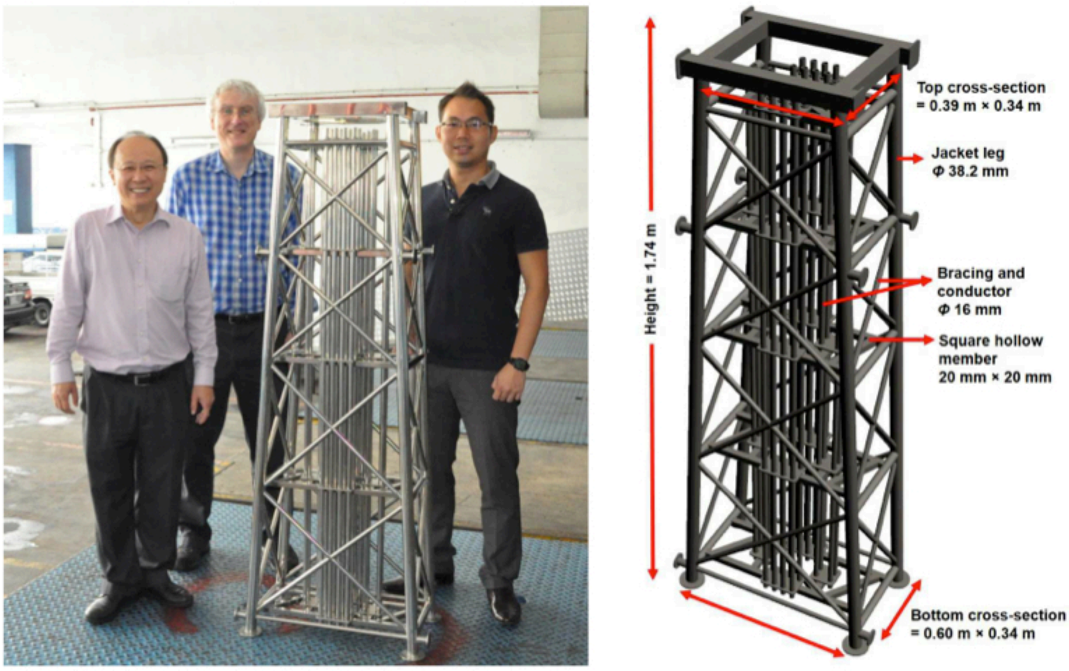

Figure 2: Left photograph shows the jacket model with three of the authors. Right picture shows a 3D CAD model of the jacket with relevant geometric information.

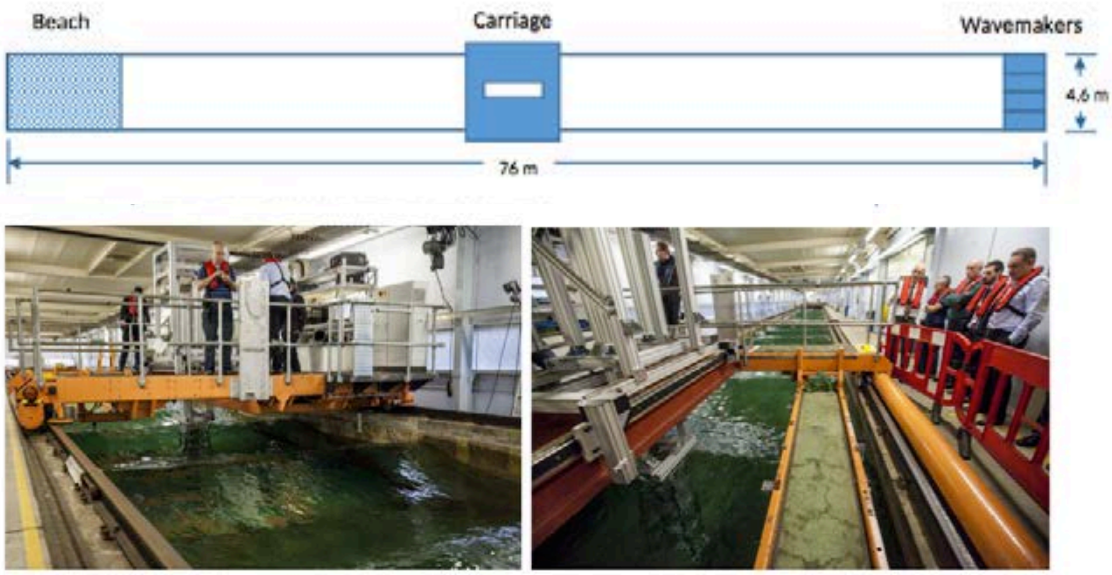

Figure 3. Top panel shows the plan view of the towing tank facility (not to scale). Bottom panel shows two photographs of the tank. Left photograph depicts the carriage with the jacket model underneath when viewed in a downstream direction along the tank where a regular wave train is incident onto the lattice model (visible below the orange carriage). Right photograph shows a closer look at the carriage, part of the double pendulum mounted on the carriage, and the lattice model beneath, now viewed in an upstream direction along the tank.

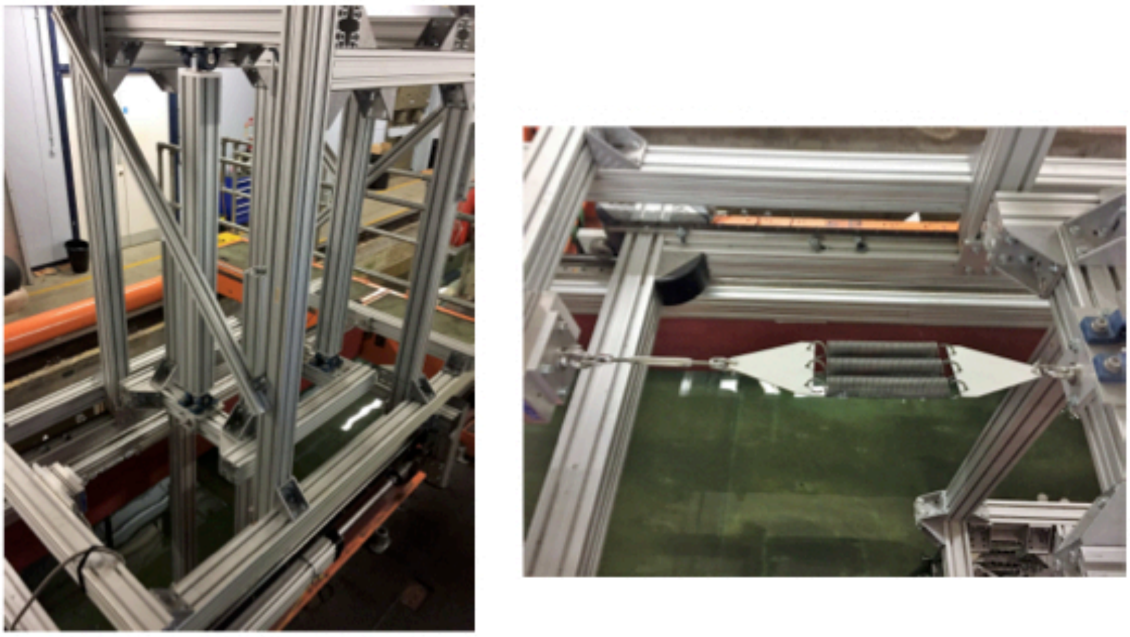

Figure 4: Left panel shows the double pendulum setup on the carriage to support the jacket model. Right panel shows the spring arrangement between the table of the double pendulum and the external support structure, producing a ratio of the structural resonant frequency to the spectral peak of the incident waves of 2.4x.

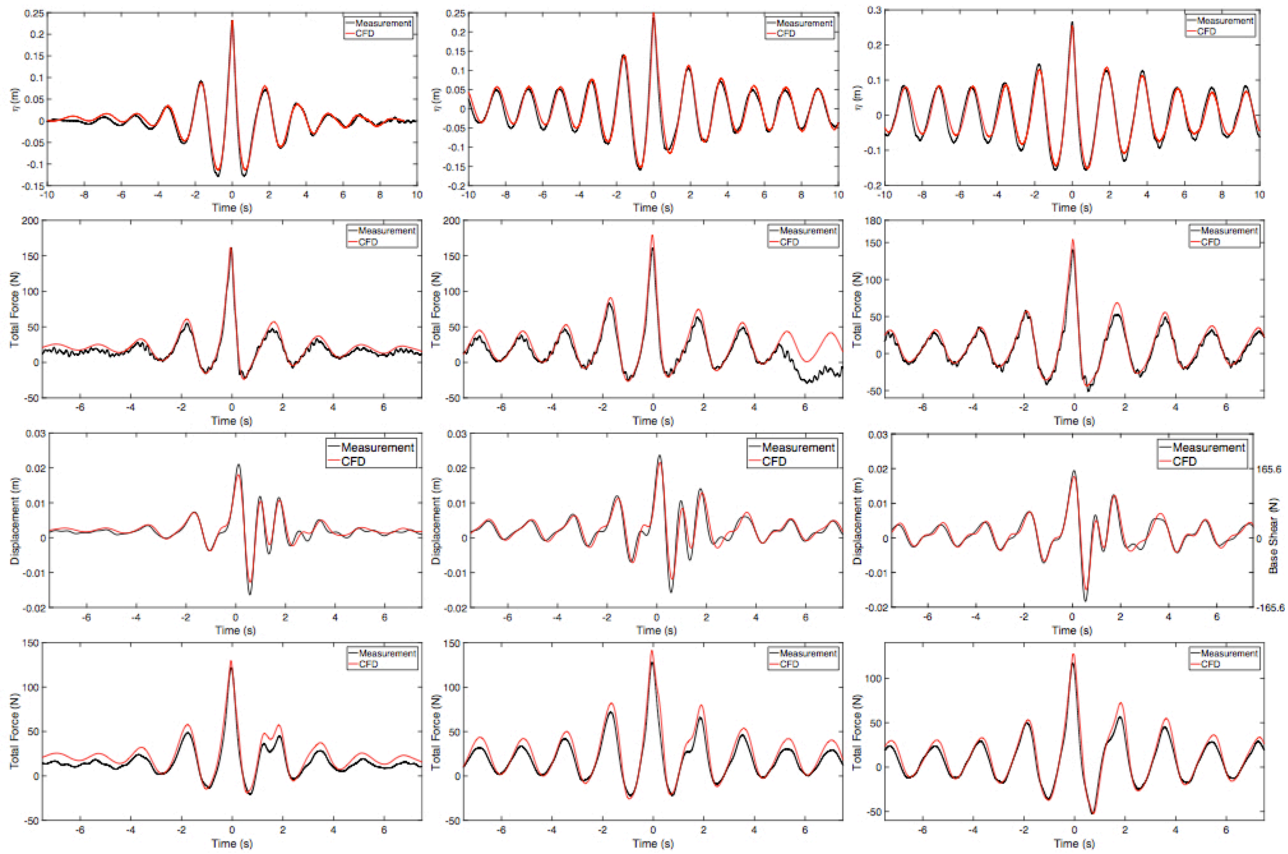

Figure 5: Comparison between numerical predictions and measurements in terms of: Free surface elevation (top row), total horizontal applied load for the stiff statically responding structure (second row), model displacement (third row), and total reaction force from dynamic tests with the spring arrangement (bottom row). The base shear at the right axis of model displacement is the reaction force to ground. Three cases are presented: a focussed wave group with a 0.28 m/s current (left panels), an embedded focussed wave group in a 0.1 m regular wave background with 0.28 m/s current (middle panels), and a 180° phase shift to embedded wave group in 0.15 m regular wave with 0.14 m/s current (right panels).

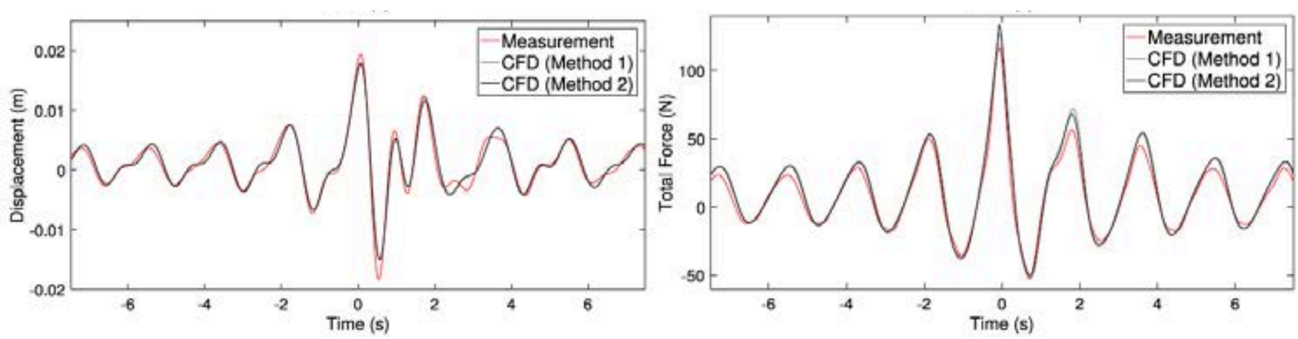

Figure 6. Structural displacement (left) and total base shear (right) for the experiment of a large embedded wave crest within a small background regular wave and a 0.14 m/s current. CFD method 1 is full coupling, method 2 used the splitting approximation for the Morison relative velocity form into the force on the fixed structure and a flow dependent damping term followed by a non-coupled structural analysis for the 1-DOF structural model.

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