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Wave-current Blockage: Reduced Forces for the Re-assessment of Ageing Space-frame Offshore Structures

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Abstract

This paper summarises extensive research work on the accurate calculation of extreme loads from waves and current on space-frame offshore structures. Although relevant to new builds, improved prediction of extreme loads is also key to the re-assessment of old and ageing offshore platforms.

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 model to account for this ‘current blockage’ was first by Taylor [1], and incorporated into standard industry practice (API, DNV and ISO). This is a simple improvement to the original Morison equation (Morison et al. [2]), which predicts forces using the undisturbed open ocean flow properties.

New work shows that unsteady large waves on top of a steady current introduces additional blockage, interpreted as wave-current blockage. Large-scale laboratory experiments have been used to validate numerical force calculations. This paper describes a numerical Computational Fluid Dynamics (CFD) model of a porous block with embedded Morison drag and inertia stresses distributed over the enclosed volume of the space-frame as a global representation. At a local 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 obstacle. Since the Morison equation is semi-empirical, drag and inertia coefficients are still required, consistent with present industry practice. This new method should be useful for assessing the overall structural load resistance and integrity in extreme wave and current conditions when survivability is in question.

Results are presented from recent large-scale experiments on a scaled (1:80) jacket model in the Kelvin Hydrodynamics Laboratory in Glasgow. These tests cover force measurements on both a jacket (stiff, statically-responding) and the same model restrained on springs to mimic structural dynamics (the first mode of a deep-water jacket, the second mode of a compliant tower or the first mode of a jack-up). For a

jacket structure under all range of wave and current conditions, only a single pair of values of Morison drag and inertia coefficients is required to reproduce the complete total force-time histories on the jacket model. This is in contrast to the present industry practice whereby different Morison drag coefficients are required in order to fit the measured peak forces over the wide range of cases considered. For the dynamic tests, we find that the relative velocity formulation of the Morison equation for space-frame structures is valid for dynamically sensitive structures. All of these effects can be captured using our numerical porous block model.

Nomenclature

F_D, F_I	= drag and inertia force, respectively
C_d, C_m, C_a	= Morison drag coefficient, inertia coefficient, and added mass coefficient, respectively
u_w, \dot{u}_w	= wave orbital velocity and acceleration
u_c	= current velocity
ρ	= water density
A, A_f, V	= solid drag area, frontal area and volume of a structure, respectively
$x_s, \dot{x}_s, \ddot{x}_s$	= structural/system displacement, velocity and acceleration, respectively
m, c, k	= structural/system mass, damping and stiffness, respectively

Introduction

Accurate calculation of extreme hydrodynamic forces from waves and current on space-frame offshore structures is important, in particular when survivability is in question. Although relevant to new builds, improved prediction of extreme loads is also key to the re-assessment of old and ageing offshore platforms. This paper summarises extensive research work aimed at accounting for blockage effects due to waves and current on offshore structures.

The Morison equation has been used extensively to predict hydrodynamic forces on space-frame offshore structures (Morison et al. [2]). It consists of drag (F_D) and inertia (F_I) force components, expressed as:

$$F = F_D + F_I$$

$$F = \frac{1}{2} \rho C_d A (u_w + u_c) |u_w + u_c| + \rho C_m V \dot{u}_w \quad (1)$$

where the Morison drag and inertia coefficients (C_d and C_m) are to be empirically determined. As is obvious from the equation, the forces are predicted using the undisturbed open ocean flow properties. However, 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 hydrodynamic forces, in particular for the drag force component. This ‘current blockage’ phenomenon was first introduced by Taylor [1], who proposed a simple analytical current blockage model to account for the blockage effect due to steady current only. The simple model is expressed as:

$$u_{cs} = u_c \left(\frac{1}{1 + \frac{C_d A}{4 A_f}} \right) \quad (2)$$

where u_{cs} is the shielded (disturbed) current velocity. This model was subsequently incorporated into standard offshore industry practice as blockage factors (e.g. see API RP 2A [3]), as a simple improvement to the original Morison equation.

Our research shows that the presence of unsteady large waves on top of a steady current introduces additional blockage, interpreted as ‘wave-current blockage’. This work was largely motivated by the findings from Allender and Petrauskas [4], who measured the peak forces on a complete 3 m high model of a Gulf of Mexico platform in regular waves and current in a very large wave tank. Using the then standard design methodology (before the simple current blockage model), they reported the necessity to use a lower value for the Morison drag coefficient ($C_d = 0.7 - 0.8$) in order to fit the measured peak forces for waves with in-line current. In contrast, for regular waves without current, a higher C_d of 1.3 – 1.6 was required instead. Their observations, which we interpreted as due to significant wave–current blockage, motivated us to re-visit the whole hydrodynamic problem of flow through space-frame structures.

Some developments on the analytical model of wave-current blockage suited for regular waves with in-line current, and recently of ‘wave-current-structure blockage’ with additional regular structural vibrations, have been reported in Taylor et al. [5] and Santo et al. [6] – [7], coupled with extensive validation in small-scale laboratory experiments. A notable result from wave-current blockage modelling is the following drag force-time history prediction applicable for $u_c/u_w \ll 1$ (a representative of an extreme condition), expressed as:

$$F_D = \frac{1}{2} \rho C_d A u_w^2 \cos \varphi |\cos \varphi| + \frac{\pi}{4} \rho A_f u_c^2 |\cos \varphi| \quad (3)$$

where φ is the phase of the regular wave. Notice the absence of $u_w \times u_c$ term, and the different form of the current drag term; this reflects fundamental differences from the Morison equation and the simple current blockage model (so the present industry practice). Although convenient, the analytical models are approximations, and are not really suitable for practical industrial applications, in particular whereby real ocean waves are never regular and the free-surface fluctuates vertically.

Given recent advances in numerical modelling, we can now use Computational Fluid Dynamics (CFD) as a tool to model and simulate the hydrodynamic forces on a realistic model of an offshore jacket. This paper will introduce the numerical tool, as well as extensive validations at large-scale laboratory experiments. Results from two types of tests will be discussed: a statically-responding jacket model (stiff) and the same model restrained on springs (dynamically-responding) to mimic structural dynamics (the first mode of a deep-water jacket, the second mode of a compliant tower or the first mode of a jack-up leg). This paper will end with discussion on the significance and potential use for practical industry application, in particular for re-assessment of old and ageing offshore platforms.

Numerical CFD-based Approach

Given the present state of technology, it is still impossible to accurately simulate the flow around a complex space-frame structure and to resolve accurately the individual wakes for every member and the global wake for the entire structure using CFD. Therefore, instead, we choose to simulate the global effect but to distribute the flow resistance of the members smoothly across the entire enclosed volume of the structure. In doing so, we still require the use of Morison equation and the empirical Morison drag and inertia coefficients, C_d and C_m .

A porous block with embedded Morison drag and inertia stresses distributed over the enclosed volume of the space-frame as a global representation is modelled in a numerical CFD calculation. At a local member scale, the standard Morison equation is used, but on the local flow. This local flow speed is reduced (disturbed) because of overall interaction between the structural members interpreted as resulting from a distributed array of obstacle. The use of local flow kinematics is in sharp contrast to the standard Morison approach which uses the undisturbed (free-stream) flow kinematics. This CFD-based approach has been implemented in a numerical wave tank based on the open-source software OpenFOAM (www.openfoam.org) and waves2foam (Jacobsen et al. [8]), see Figure 1 and Santo et al. [9] – [14].

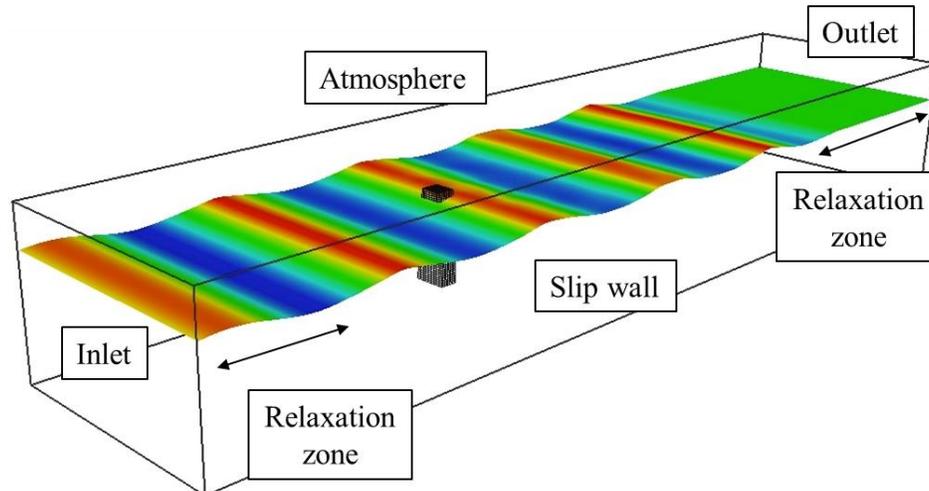


Figure 1: Layout of the computational domain. The location of a porous tower is indicated as black block. A regular wave is shown propagating from the inlet to the outlet. Red colour represents wave crests, blue represents wave troughs, and green represents water surface close to mean sea level. Also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

Previously the proposed numerical approach has been validated with a smaller laboratory scale test on a truss frame structure subjected to regular waves with in-line sheared current (Santo et al. [11]). Good agreement further motivates the study to account the effect of transient and non-periodic waves which are more representative of large waves on the open sea. To model the transient effects, we use focussed wave groups, and, to account for the presence of large waves in an on-average smaller sea-state, we embed these focussed wave groups within a smaller regular wave background. The larger scale tests to be described next serve as a series of benchmarks to validate the proposed approach using a more realistic space-frame model.

Validations at Large Laboratory Scale

A 1:80 scale jacket model has been tested in a large towing tank in Kelvin Hydrodynamics Laboratory of University of Strathclyde in Glasgow in two series of tests in 2016 and more recently in 2017, see Figure 2. The jacket is modelled after a typical second-generation 4-legged North Sea platform operating in 115 m water depth, see Figure 3. In the experiments, the jacket is suspended below a carriage, which is then towed on a constant speed to simulate uniform current onto the model. The same jacket is then subjected to a range of isolated wave groups made to focus at the jacket position, and  e groups embedded in a smaller regular wave backgrounds, all with different in-line current speeds. The global base-shear type load in waves and current was measured, both with the jacket very stiff (static response) and also with it allowed to move on springs (dynamic response).

Static Case

During the first series of tests, the jacket model was supported rigidly from the carriage (hence statically-responding structures), and the global horizontal hydrodynamic force - time histories were recorded

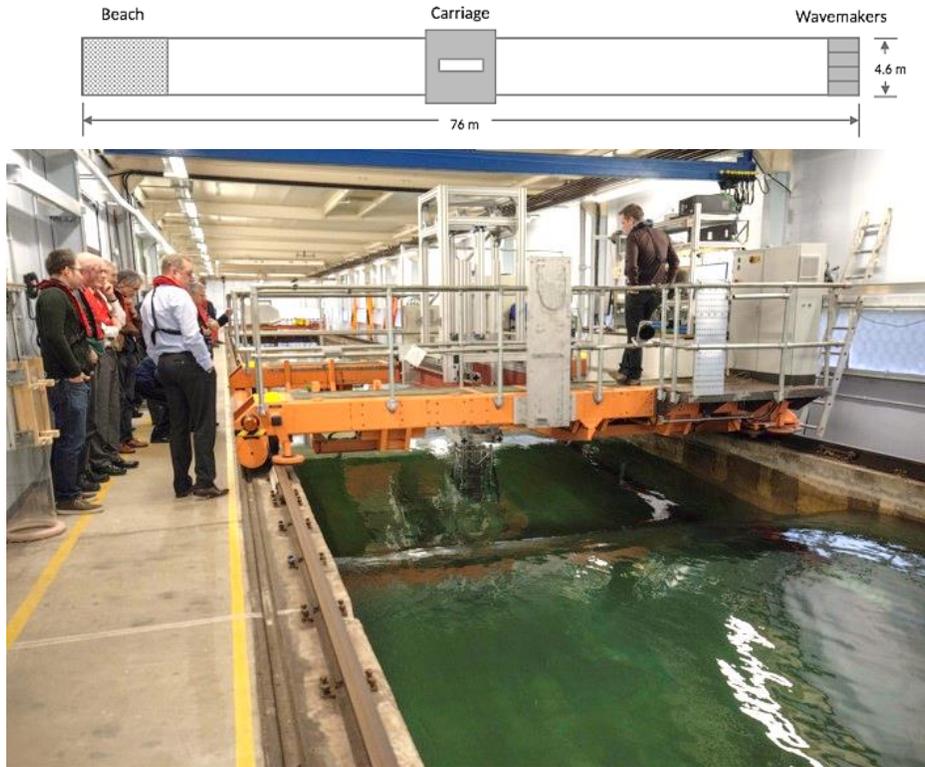


Figure 2: Top panel shows the plan view of the towing tank facility (not to scale). Bottom panel shows a photograph of the carriage when viewed in a downstream direction along the tank. On the carriage, a parallel pendulum system supports the jacket model below.

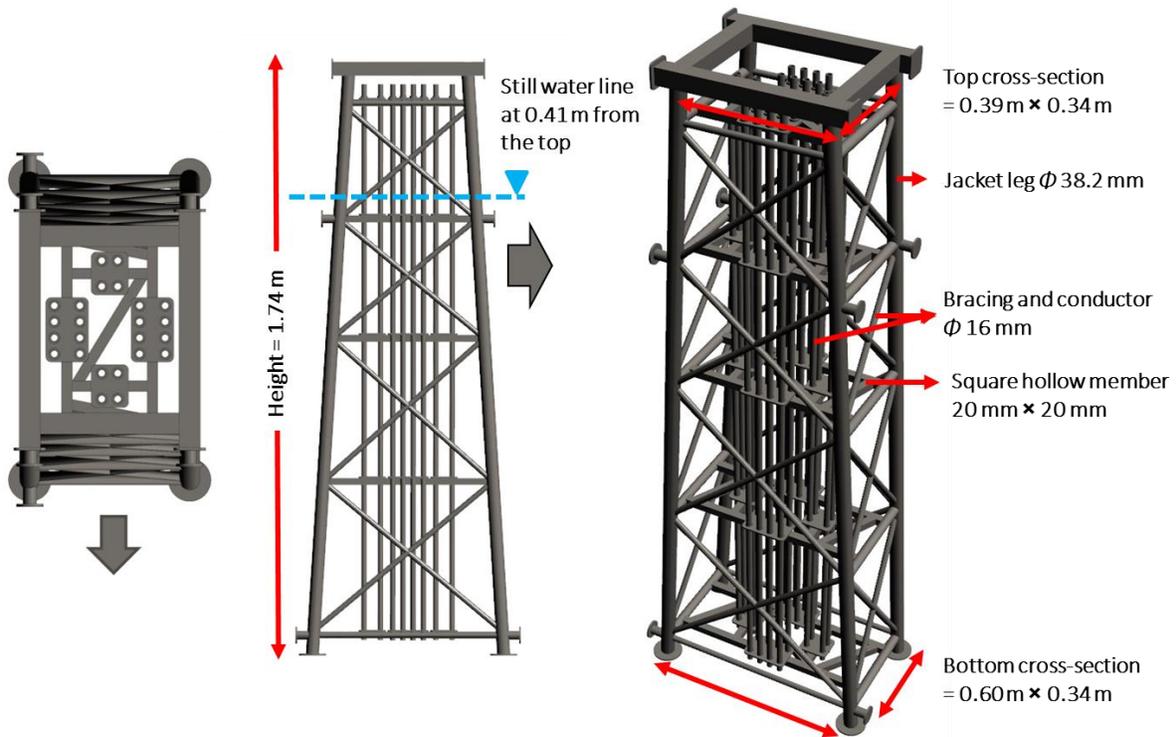


Figure 3: From left to right: a plan view, side view and 3D view of the jacket model with relevant geometric information.

through a force transducer. The surface elevation - time histories next to the model were also measured. A porous block as a proxy to the actual jacket model was set up numerically, and the same incident wave conditions in a numerical wave tank were modelled and simulated. The numerical predictions on the total force - time histories compare well with the measurements for all range of cases with a single and

consistent values of Morison coefficients of $C_d = 1.3$ and $C_m = 2.0$, without any observed Keulegan-Carpenter (KC) number effects so long as the steady current is present, see Figure 4. It is worth emphasising that for the present industry practice (or standard Morison equation)  the peak forces for all cases, different C_d values would be required, consistent with Allender and Petruskas [4]. This work is reported in Santo et al. [12].

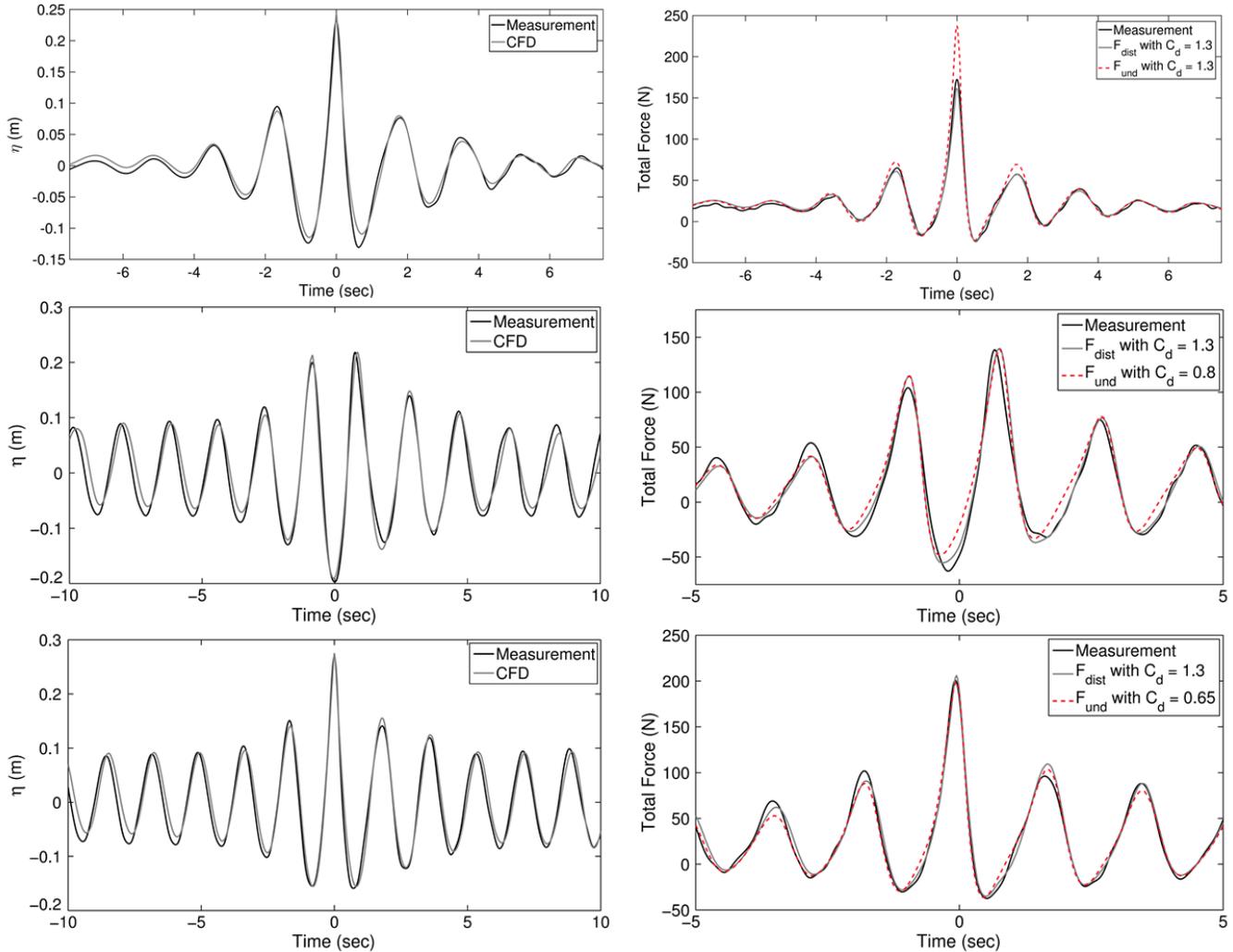


Figure 4: Comparison of surface elevation (left) and total force (right) time histories between measurements (black) and numerical predictions (grey and red) for three cases. Top panel is for a focussed wave group with 0.28 m/s current. Middle panel is for an embedded focussed wave group in 0.15 m regular wave with 0.14 m/s current. Bottom panel is for a 180 deg phase shift to embedded wave group in 0.15 m regular wave with 0.28 m/s current. For the total force comparison, F_{dist} is the force prediction using the porous block approach accounting for wave-current blockage. On the other hand, F_{und} is the force prediction due to API RP 2A which only accounts for current blockage. For 1:80 scale, 0.14 and 0.28 m/s current correspond to 1.25 and 2.5 m/s at field-scale, while 0.25 m crest elevation corresponds to 20 m at field-scale, which is a representative of an extreme wave condition. The maximum total force of 200 N at lab scale corresponds to 100 MN at field-scale.

Dynamic Case

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 5. Two different springs were considered, which yield frequency ratio $\sim 1.9 \times$ (spring 1) and $2.4 \times$ (spring 2) between the structural mode and the incoming wave. Since the focus was to explore the excitation of a high frequency vibration modes relative to the wave natural frequency, these tests should be of relevance to the second

mode of compliant towers, and the first mode of both a deepwater dynamically sensitive jacket and jack-ups in intermediate water depth.

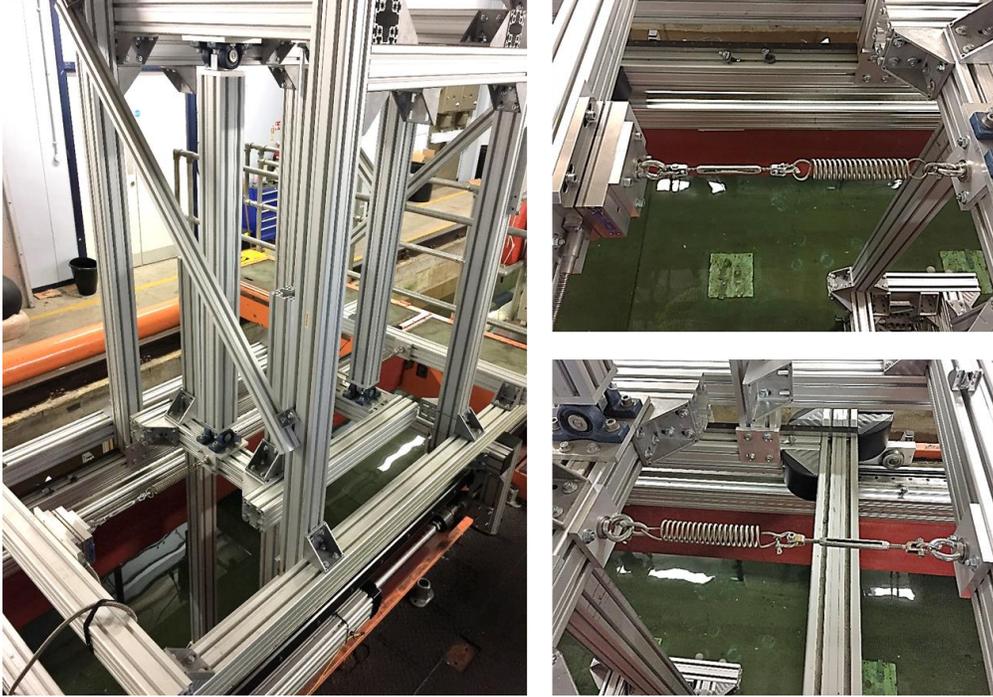


Figure 5: Left panel shows a photograph of the double pendulum setup on the carriage to support the jacket model. Right panel shows photographs of the spring 1 arrangement at the front of the setup which is then connected to a force transducer (top), and at the rear of the setup (bottom).

It should be noted that experimentally the model horizontal displacement is very close to uniform with depth (a single mode of vibration), due to the way the model is supported from the carriage in the towing tank. The global force – time histories through the springs (or, equivalently, the force to the ground) were measured using 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 transfer function derived from an equation of motion of a single degree-of-freedom (DOF) oscillator, given by: $m\ddot{x}_s + c\dot{x}_s + kx_s = F$, where F is the external force acting on the system. Apart from the water surface elevations, the model displacement – time histories were also recorded using a Qualysis motion tracking system. The jacket model was subjected to essentially the same set of incident wavefields and currents as before.

For the comparison with the dynamic tests, a porous block with distributed stresses according to the local Morison equation with the relative velocity formulation is now used, which is expressed as:

$$F = F_D + F_I$$

$$F = \frac{1}{2}\rho C_d A(u - \dot{x}_s)|u - \dot{x}_s| + \rho C_m V \dot{u}_w - \rho C_a V \ddot{x}_s \quad (4)$$

where u is now the combined wave and current velocity, $(u_w + u_c)$. When combined with the equation of motion of a single DOF oscillator, the following expression can be obtained:

$$M\ddot{x}_s + c\dot{x}_s + kx_s = \frac{1}{2}\rho C_d A(u - \dot{x}_s)|u - \dot{x}_s| + \rho C_m V \dot{u}_w \quad (5)$$

where M is now the total mass of the system which includes the added mass effect.

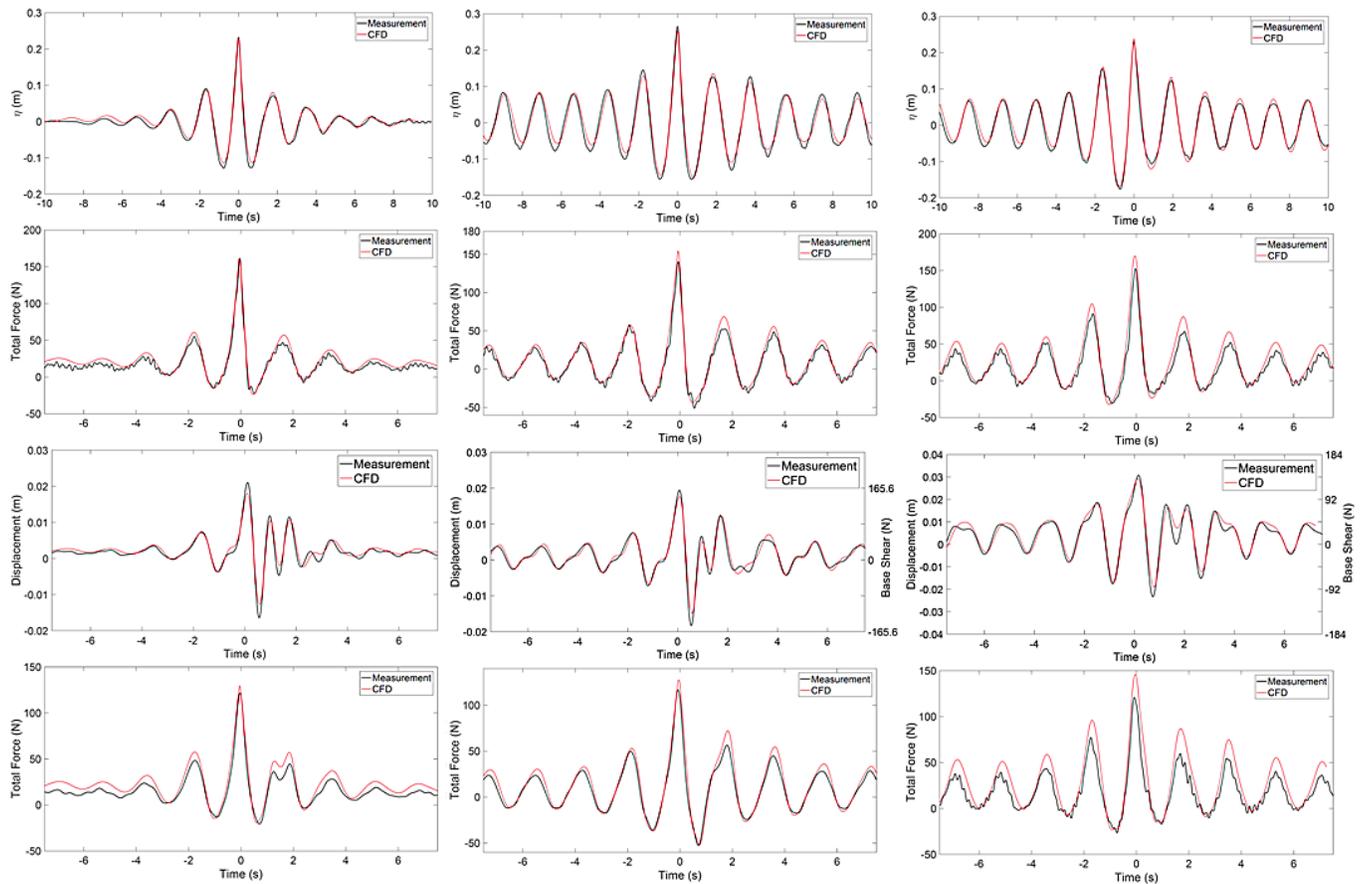


Figure 6: Comparison between numerical predictions and measurements in terms of: surface elevation (top row), total force from static tests (second row), model displacement (third row), and total force from dynamic tests (bottom row). The base shear at the right axis of model displacement is the reaction force to ground. Three cases are presented: a focussed wave group with 0.28 m/s current (left panel), a 180 deg phase shift to embedded wave group in 0.15 m regular wave with 0.14 m/s current, and an embedded focussed wave group in 0.13 m regular wave background with 0.14 m/s current (right panel). The results from the dynamic tests are obtained from 2 different spring arrangements: spring 2 for the left and middle panels, and spring 1 for the right panel.

The agreement between the numerical results and the measurements are encouraging in all cases with current and using the same sets of C_d and C_m coefficients as before, see Figure 6. 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, see Figure 7. This is significantly larger than the normally assumed values of 2-3% of critical damping, as recommended by API for example, and also much larger than the $\sim 1\%$ of critical damping observed in our push-tests in still water. This additional damping can be viewed as arising from a considerably reduced hydrodynamic force, a realisation of wave-current-structure blockage effects. Further details are given in Santo et al. [13 in review].

From laboratory to field scale, one question remains; whether in the very high Reynolds number flow at field scale a similar notable increase in damping due to the relative velocity effect would occur. We believe the only change beyond Froude scaling from the laboratory to the field would be the choice of suitable Morison coefficients. In our large scale experiments, the optimum C_d is ~ 1.3 ; high yet reasonable because there is no account for local velocity amplification due to the presence of other members, in particular due to the closely-spaced conductors, and the horizontal framing in the model consists of square box section with a higher C_d than the rest of the cylindrical members in the model. At field scale, $C_d \sim 1$ is recommended, which is largely based on the early measurement of current blockage on the Bullwinkle platform by Forristall [15].

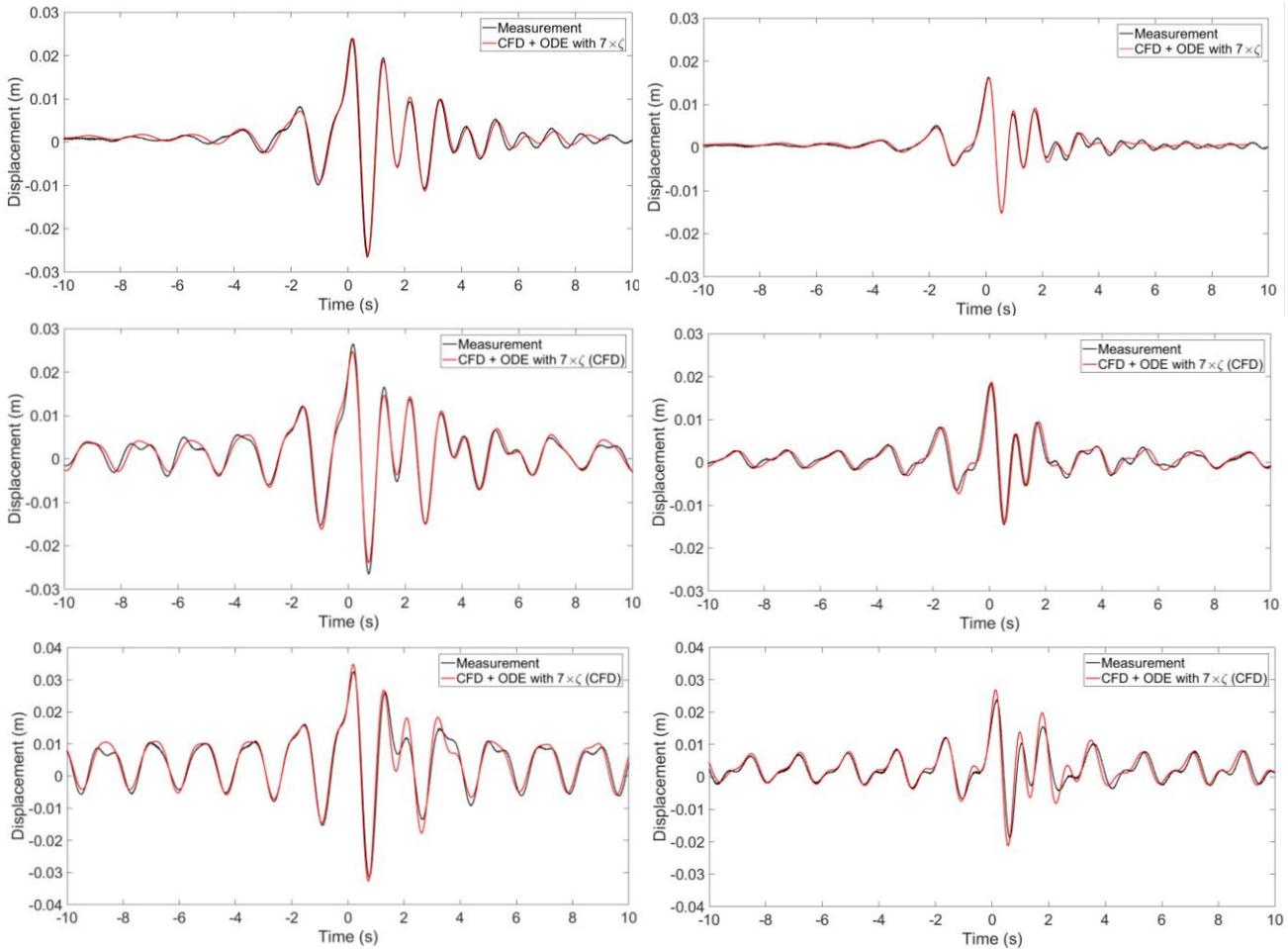


Figure 7: Comparison of surface elevation time histories between measurements from dynamic tests (black) and numerical predictions (red) with spring 1 (left) and spring 2 (right) arrangement for three cases. The numerical results are obtained by applying the predicted static force from CFD into an external time-domain ODE model (in MATLAB) with an artificial damping rate equivalent to 8% of critical damping. Top row is for a focussed wave group with 0.14 m/s current. Middle row is for an embedded wave group in 0.14 m regular wave with 0.14 m/s current. Bottom row is for a 180 deg phase shift to embedded wave group in 0.15 m regular wave with 0.28 m/s current.

Another question is on the effect of a directionally spread wavefield. The entire study is focussed on unidirectional (long crested) sea consisting of waves with in-line current, which represents the worst (most extreme) case scenario. The presence of directional spread sea would reduce the kinematics (e.g. see kinematic reduction factor due to directional spreading in API RP 2A [3]) and hence the associated hydrodynamic force.

Discussions on the use of CFD

Static Case

It is worth stressing that a universal form of reduction factors to reduce the undisturbed flow kinematics to account for wave-current blockage, similar to reduction factors for current blockage given in the design standard API RP 2A [3], cannot be obtained. Therefore, it is necessary to solve for the blocked (or disturbed) kinematics accounting for the presence of the structure using numerical CFD simulations. The necessity is slightly complicated by the fact that wave-current blockage is not only geometry dependent, but also kinematics dependent, as opposed to the simple current blockage (and the present industry guidelines) which is only geometry dependent. If the aim is to represent transient flow dynamics in all

possible cases, the only way to obtain actual force – time histories is to time-march the Navier-Stokes equations with the embedded local Morison equation (with local disturbed kinematics).

Dynamic Case

Although the jacket model moved in free vibration in the actual physical tests, there is no moving mesh involved in the numerical modelling of the dynamic case. A time-varying stress in a porous block is implemented instead according to the local Morison equation with relative velocity formulation (see Equation 4), and the governing equation is solved with a static computational mesh domain just as the static case.

Two methods have been implemented to obtain the numerical force predictions for the dynamic case. The more sophisticated method (our gold standard) requires coupling the fluid solver code, based on the local Morison with relative velocity formulation (Equation 4), with an internal time-domain ODE solver, based on the equation of motion of a SDOF oscillator (Equation 5), 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 for example USFOS (www.usfos.no), not impossible but this would be quite challenging to achieve efficiently.

A much better practical approach, but slightly less sophisticated, is an approximation which allows for an expansion of the Morison relative-velocity form (hence a de-coupling), as given by Haritos [16] and Merz et al. [17]. This has the form:

$$\begin{aligned} F_D &= \frac{1}{2} \rho C_d A (u - \dot{x}_s) |u - \dot{x}_s| \\ F_D &\approx \frac{1}{2} \rho C_d A (u|u| - 2|u|\dot{x}_s) \end{aligned} \quad (6)$$

The approximation works well so long as the structural velocity is smaller than the disturbed (wave + current) flow kinematics, which essentially holds for all the practical structural vibration modes of interest. Under this circumstance, the equation of motion can be further simplified to be:

$$M\ddot{x}_s + (c + \rho C_d A |u|)\dot{x}_s + kx_s = \frac{1}{2} \rho C_d A u |u| + \rho C_m V \dot{u}_w \quad (7)$$

where the force term on the right hand side of the equation is the applied force from the static case (rigid connection, so the statically-responding structure assumption). Both methods agree very well for all of the cases we tested, and with the measurements.

This second method allows us to essentially separate the fluid dynamics OpenFOAM run from the structural analysis run in any of the typical structural analysis software, so there is no requirement to simultaneously run both codes. The results from OpenFOAM run on static cases can simply be post-processed into a convenient form and stored in a library. This includes what is required for estimating the change in fluid loading due to the structural motion. All of this pre-computed hydrodynamic information would then be imported into the structural analysis software to perform a full dynamic push-over analysis with time-marching of the collapse behaviour with realistic hydrodynamic forces at all times. Thus, it is this second method that we recommend should be developed for practical industrial adoption.

Clearly the internal representations of the global hydrodynamic loads are very different in OpenFOAM and a typical structural analysis software such as USFOS. In our OpenFOAM representation using porous

blocks, the individual structural elements are not resolved, only their bulk effect in terms of the local flow field, the hydrodynamic forces and the coefficients averaged over the structure. To interpret this bulk effect from OpenFOAM to USFOS, the information transfer would probably be done on a frame-by-frame basis, perhaps with higher resolution close to the free-surface. All of these loads need to be transferred into either nodal or member forces on the USFOS frame model, depending on whether global or local failure is more dominant/important.

Conclusions

A summary of extensive research work on wave-current blockage has been presented. For the static case, there is clear additional reduction in the applied hydrodynamic force relative to the simple current blockage (and present industry practice such as API RP 2A) or standard Morison approach. For the dynamic case, this can be viewed as either a reduction in the applied hydrodynamic force due to the relative velocity formulation in the Morison equation, or equivalently a substantial increase in structural damping. All of these blockage effects can be adequately captured using our proposed modelling approach using a porous block as a global representation of a space-frame offshore structure, with embedded local Morison stresses distributed over the volume of the structure and simulated in the context of CFD. The large-scale experiments in Glasgow serve as an extensive validation to the proposed approach.

This paper ends with discussion on the possible use of the proposed approach for practical industry applications. Particularly for the dynamic case, the use of the approximation to the Morison relative-velocity formulation allows a de-coupling between fluid dynamics codes, such as OpenFOAM, and structural dynamic codes, such as USFOS. The results from OpenFOAM run on static cases can be post-processed, stored, and imported to USFOS code to perform full dynamic push-over analysis of the collapse behaviour with realistic hydrodynamic forces at all times. This method should be of significance for practical industry applications in particular for re-assessment of old and ageing offshore platforms.

Two pieces of work would be of immediate interest. Having accurately defined the extreme hydrodynamic forces, the first follow-on study would be to perform a full dynamic push-over analysis using USFOS on three types of structure: dynamically-sensitive deep water jackets, compliant towers and jack-ups. Noting that our accurate representation of hydrodynamic forces is only applicable for a substructure, the other follow-on study would be to examine what happens when a particular wave reaches the deck level (superstructure), commonly known as wave-in-deck.

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