# FLEXIBLE FLUID-STRUCTURE INTERACTION OF A FLEXIBLE PLANT MODEL FOR NATURE-BASED SOLUTIONS

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Nature-based solutions (NBS) represent a new field of research and engineering applications, becoming increasingly popular in the coastal engineering field. Salt marsh restoration, an example of NBS, is particularly appealing due to the variety of benefits they can provide, especially their capacity to induce sediment accretion, potentially keeping pace with sea-level rise. This study investigates the applicability of the flexible fluid-structure (FSI) interaction module being developed for open-source software REEF3D to the motion of marsh plants under wave action using data from a physical model study performed by Paul et al. (2016). The model consistently overestimates the drag force response of a flexible plastic plant surrogate under wave action. This suggests that this new tool may not be suited for this case. However, further investigation must be performed to test the limits of the model's application.

Keywords: nature-based solutions; REEF3D; flexible FSI modelling, CFD

## INTRODUCTION

Nature-based solutions (NBS) comprise new methods and design ideas that utilize natural systems to protect shorelines. An example of NBS, living shorelines are typically constructed or restored saltmarshes or mangroves. These engineered ecosystems can attenuate incoming waves and floods (Garzon et al., 2019a), filter water, absorb atmospheric carbon, and have the potential to accrete sediment on pace with sea-level rise, thus providing successful coastal protection along with co-benefits in the form of climate change adaptation and ecological enhancements (Short et al., 2016). However, their applicability depends on a range of factors, including wave conditions, climate, nutrient availability, among others.

Numerical modelling studies of saltmarshes tend to represent the vegetation field in two distinct ways. The first is as areas of increased friction. Examples of this approach include Chakrabarti et al. (2017) and Garzon et al. (2019b). These studies use flume- or field-calibrated drag or friction coefficient values and apply them to the vegetated area. The added drag forces replicate the effect the marsh or mangrove would have on the local hydrodynamics. The second approach is representing marshes as arrays of rigid cylinders. Studies using this method include Arunakumar et al. (2019) and Vuik et al. (2018). This approach assumes that rigid, cantilevered beams can represent plants and approximate the influence of plants on waves. The dimensions of the cylinders come primarily from fieldwork measuring the plants in question (Vuik et al., 2018). These methods can be effective with appropriate calibration but do not capture the dynamic motion characteristics of the plants.

Other studies exist modelling vegetation as fields of flexible bodies. These are relatively uncommon, given the comparatively high computational cost of this approach. Two examples are known to the authors: the work of Marjoribanks et al. (2017) and that of Mattis et al. (2019). The former investigated canopy mixing under 1D flow. The latter modelled wave attenuation capacity of saltmarsh vegetation. Neither of these studies investigated the accuracy of the plant models themselves, instead focussing on their effect on the surrounding hydrodynamics.

Though saltmarshes are relatively common, little is known about the flow within them, especially under wave action. Factors such as sheltering, the process by which plants upstream divert flow away from those immediately downstream, make the modelling of full marshes extremely difficult and computationally expensive. Therefore, most research investigating marsh plant drag and movement has been done using individual plants.

The movement of marsh vegetation under wave action is another aspect that makes these systems challenging to model effectively. Marsh plants may sway (symmetrical motion) or move in a whip-like manner (asymmetrical) as waves pass, changing how they affect the flow at any given moment (Rupprecht et al., 2017; Ghisalberti & Nepf, 2002). By accurately replicating plants' movement, also

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called reconfiguration, in response to waves, the understanding of this dynamic behaviour may be improved. Furthermore, if a numerical model can be demonstrated to accurately replicate the behaviour of a saltmarsh plant or plants under a variety of conditions, the calibration requirements for future numerical modelling efforts may be lessened.

## OBJECTIVES

This study contributes to a larger, ongoing research project which aims to develop design guideline for NBS in Canada. By expanding the understanding of the behaviour of the vegetation that makes up marshes, it is hoped that these systems can be designed and implemented more effectively by coastal zone practitioners, increase the confidence of planners and legislative bodies in their application, and encourage their use whenever feasible.

This study is a numerical investigation into the drag and reconfiguration of marsh plants under wave attack. Research by Paul et al. (2016) provides the physical modelling data for this study. An open-source computational fluid dynamics (CFD) software, REEF3D, was used to numerically model a pair of flexible plastic strips in a wave flume as a flexible body under regular wave conditions at fixed water levels. These structures were modelled exactly as tested in the physical model, limiting the necessary calibration to the parameters of the CFD model itself. The model's output was compared with the physical modelling work presented by Paul et al. (2016). The flexible fluid-structure interaction (FSI) module in REEF3D used in this study is currently under development, adding a further level of novelty to the work presented herein. The main objectives of this study are:

- Facilitate the development of a flexible FSI module for REEF3D.
- Investigate the effectiveness of this tool for a single flexible structure under wave action using published data from physical modelling work.

This study is limited to modelling saltmarsh vegetation surrogates as tested in the physical modelling study in terms of geometric and material properties. As no reconfiguration measurements were taken in the Paul et al. (2016) study, the evaluation focusses on the module's force output. This work is also limited to the small amplitude regular wave conditions tested in the original flume study. The waves tested herein are below 1 m in height and have a maximum period of just over 4 s. Long or extreme wave conditions are not tested in this study.

## METHODOLOGY

### REEF3D

REEF3D (Bihs et al., 2021) is an open-source CFD software produced by the Norwegian University of Science and Technology (NTNU). REEF3D has been used previously to model similar systems to moving marsh plants, namely the movement of aquaculture nets (Martin & Bihs, 2021a; Martin et al., 2020). The accessibility of open-source software was also appealing for this study, allowing the work to be built upon more easily. Finally, a time-averaged CFD software, as opposed to large-eddy simulation (LES), was determined to be ideal. Given the scale of vegetation or vegetation surrogates, it is expected that average conditions will be the primary driver of plant behaviour, as opposed to turbulent structures. As a primary step, the empirical turbulence models used in the CFD simulations in REEF3D were deemed sufficient for a first-order approximation of the plant motion.

REEF3D solves the Reynolds-averaged Navier-Stokes (RANS) equations using an Eulerian, or mesh-based approach to modelling the hydrodynamics. This scheme represents the modelled area as a fixed rectangular grid. The fluid movement through the grid elements is calculated per time increment, along with the associated forces. The level-set method is used to analyze the free surface of the fluid, allowing for moving surfaces to be modelled on the fixed Eulerian mesh. It works by setting the interface between the two fluids (air and water) to a zero contour of the level-set function, a signed distance function. This is then coupled with a convection function to resolve the flow field (Bihs et al., 2018). The RANS are further simplified by assuming the incompressibility of the fluids (Bihs et al., 2018).

The developers of REEF3D recommend using the k-ω turbulence model, specifically its shear-stress transport (SST) formulation (Martin et al., 2020; Miquel et al., 2018). This option is unique because it uses a k-ω model within the boundary layer but switches to a k-ε model in the free stream, making it applicable in a broad range of conditions. REEF3D accounts for solid boundaries using Schlichting's rough wall law (Bihs et al., 2018). This flexibility in the turbulence model has led to it producing the most robust and reliable results for a range of cases (Bihs et al., 2018).

**Fluid-Structure Interaction Modelling**

The flexible FSI module currently being implemented in REEF3D is based on the method developed by Tschisgale & Fröhlich (2020). A detailed description of how the model is used within REEF3D can be found in Martin & Bihs (2021b). Plants are simplified as long, thin strips governed by the Cosserat rod equations using a Lagrangian, or particle-based, framework (Tschisgale & Fröhlich, 2020). The specific formulation of the Cosserat rod equations used in this model is the 'geometrically exact' option, which accounts for the rigid body motion and typical deformations of cantilevered rods. The cross-section of the structure is assumed to remain rigid during the deformation of the rod (Tschisgale & Fröhlich, 2020). In this application, the Lagrangian framework is applied to the flexible structure by modelling it as a set number of particles, or markers, which are fixed together and move in relation to one another. The difference between Lagrangian and Eulerian representations is illustrated in Figure 1. Continuous direct forcing is applied to model the interactions between these strips and the surrounding fluid.

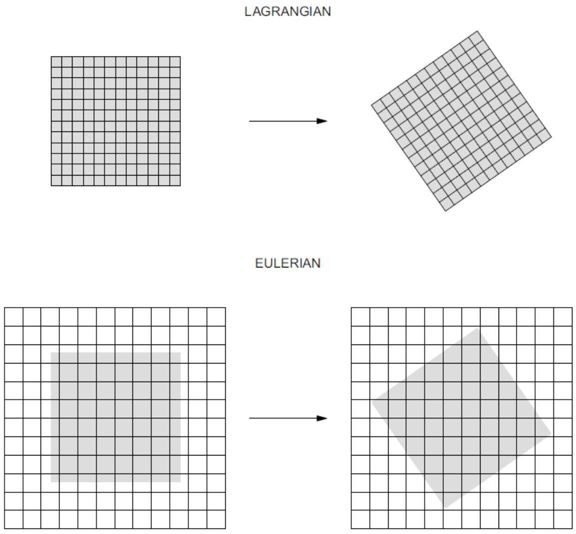


**Figure 1. Lagrangian (top) and Eulerian (bottom) modelling frameworks.**

This model assumes that the structures are completely submerged in fluid, with both the water and structure having constant material properties. The structures are assumed to be long and slender, making their longitudinal extension much larger than their cross-section. This allows the thickness to be approximated as zero within the fluid, making the structure coincide entirely with the fluid within the coupling model, while the Cosserat rod equations are still solved for the three-dimensional structure. Due to fluid loads, local deformations and internal strains are assumed to be small (Tschisgale & Fröhlich, 2020). External moments acting on the structure are assumed to be negligible due to the slender geometry of the strips (T. Martin, pers. comm., December 14, 2021).

**Physical Modelling**

To validate the effectiveness of this model for plants under wave action, data from Paul et al. (2016) on plant reconfiguration and drag under wave action was used. In this study, four different iterations of surrogate and live marsh vegetation were subjected to waves in a flume, with the drag on the structures being measured continuously during testing. The hydrodynamic conditions used were regular waves with periods ranging from 2.07-4.10 s and amplitudes between 0.17-0.89 m. The still water level during testing was 1 or 2 m. Each test lasted long enough for 11 fully-developed waves to pass over the plant surrogates. The drag force of the structure and horizontal orbital velocity at 15 cm above the platform in line with the strips were measured continuously during testing. The plastic strips were attached to a drag sensor via a metal bar, the effect of which was removed in post-processing. The experimental setup, with the numerical domain highlighted, can be seen in Figure 2.

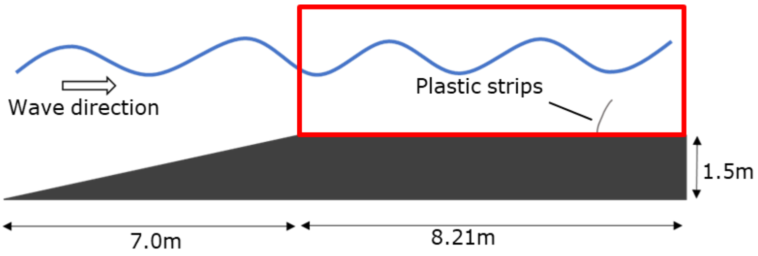


**Figure 2. Physical modelling setup of Paul et al. (2016) with numerical domain highlighted in red.**

The structure tested by Paul et al. (2016) used for validation in this study was a pair of model plant stems. The geometric and material properties of the stem can be found in Table 1. Both velocity and drag force are presented as average peak values per wave, referred to henceforth as "average."

**Table 1. Geometric and material properties of the model step (Paul et al., 2016)**

| Property | Value |
|---|---|
| Length | L = 0.25 m |
| Width | W = 5.5 mm |
| Thickness | t = 4 mm |
| Density | ρ = 1.24 g/cm$^3$ |
| Elastic Modulus | E = 3.44 GPa |

The Paul et al. (2016) study was determined to be an ideal case study for the present numerical work for the following three reasons:

1. *Strip thickness*. Only one of the four tested strip configurations is modelled numerically, namely 2-strip x 4mm-thickness. REEF3D's flexible FSI module has been found to require grid sizes equal to the flexible body thickness. Grid size is the primary driver of required computational power for modelling, so the grid size is ideally maximized.
2. *Strip geometry*. REEF3D's flexible FSI module assumes the flexible bodies to be rectangular prisms when standing upright. This is the case in those tested in the Paul et al. study, thus minimizing inaccuracies and reducing potential error related to the structures' geometry.
3. *Tested hydrodynamic conditions*. The study used regular waves as part of its testing, which is ideal for numerical efforts due to its simplicity. Furthermore, only the first 11 fully developed waves were considered for the regular wave tests, limiting the experimental time that needs to be modelled. In both cases, this lowers the required computational effort for running simulations.

## RESULTS

### Calibration

The model's sensitivity to grid size was investigated by running tests using identical wave and structure conditions with cell sizes of 0.5, 1, 2 and 3 times the thickness of the flexible body *t* (2, 4, 8 and 12mm, respectively). Beyond grid size, the results' sensitivity to the number of elements, or Lagrangian markers, for the plant structures must be analyzed. Drag force is influenced significantly by the number of elements into which the structure is divided; the movement of the structure comes from the inter-element boundaries acting as hinges. Element counts from 5-7 were tested. Results from this work are presented in Figures 3-4, showing the drag force over a single wave cycle for the above grid sizes and element counts, respectively.

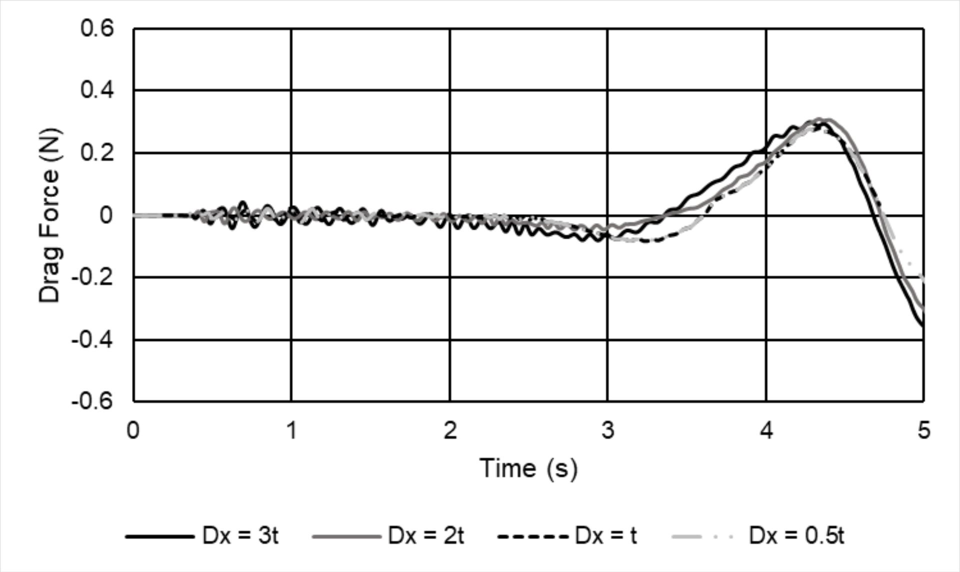


**Figure 3. Drag force for various grid sizes.**

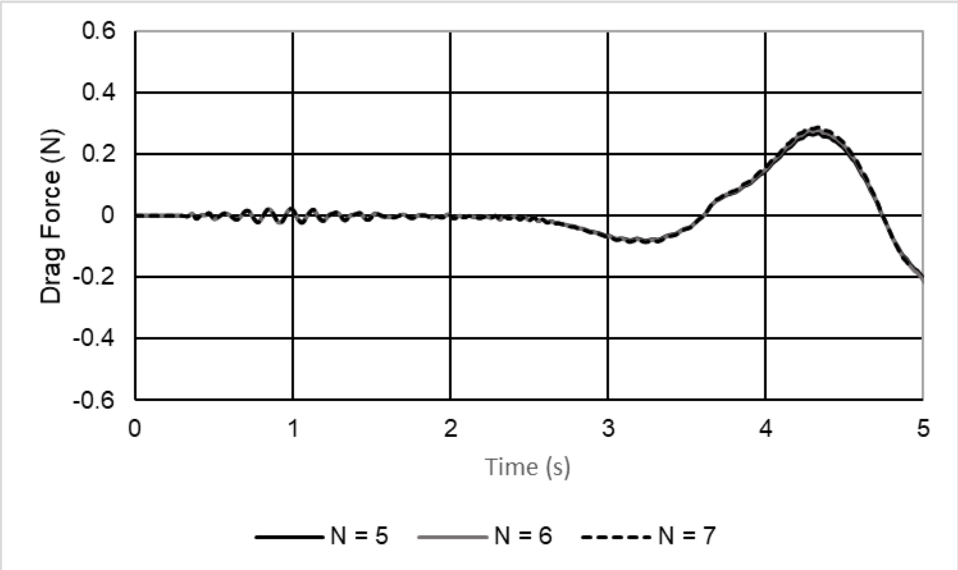


**Figure 4. Drag force for various element counts.**

The model's output converges for cell sizes smaller than 4mm, equal to the strip thickness, and element counts greater than 6. These values were therefore used for the simulations going forward.

**Validation**

The model was validated by numerically replicating the physical modelling results of Paul et al. (2016). The structure was modelled in REEF3D precisely as described in the flume study. Two plastic strips were placed 7.15 m from the start of the domain, 5 cm apart, with the physical and geometric properties described in Table 1. The average horizontal orbital velocity and drag force were compared to the physical modelling values. These are presented in Figures 5-6.

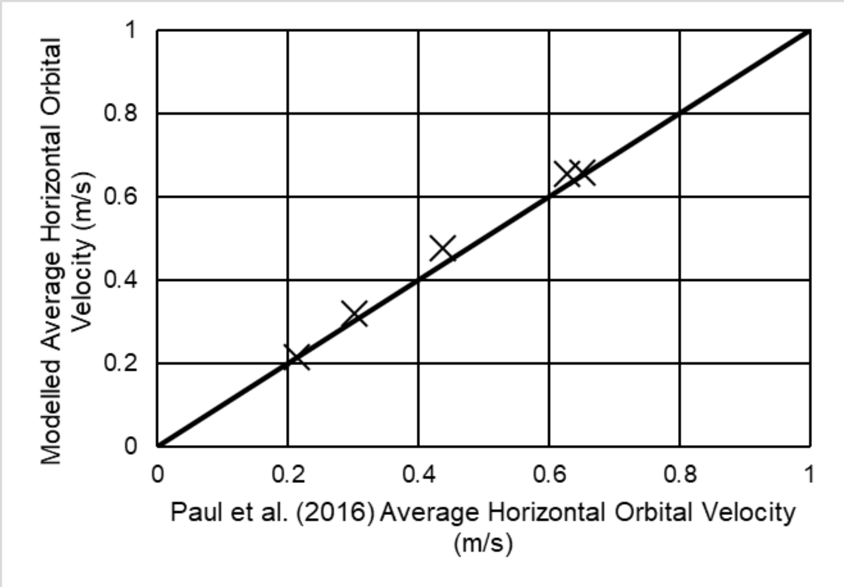


**Figure 5. Modelled vs. measured average velocity.**

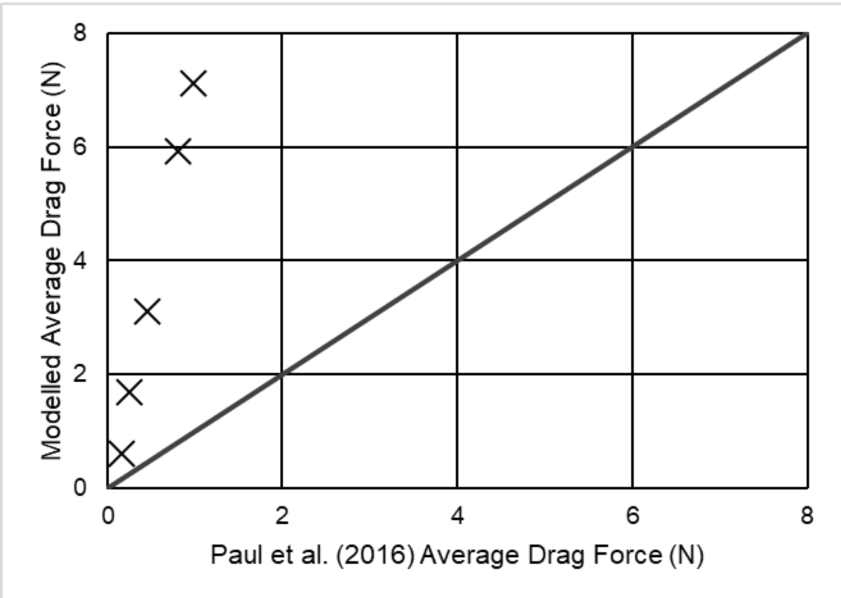


**Figure 6. Modelled vs. measured average drag force.**

The model is shown to replicate the hydrodynamic conditions well, but the drag force results are consistently overestimated. The meaning of these findings and how they may be used in future works are discussed below.

## DISCUSSION & NEXT STEPS

The new flexible FSI module currently being implemented in REEF3D has been shown to consistently overestimate the drag force response of flexible bodies under wave action under in-situ conditions. It is also seen to overestimate the drag more as the wave height and period increase rather than the force being overestimated by a constant value. If the latter were the case, a calibration value could be suggested, and the model may be effectively applied to the current case. However, this is not possible because the drag force response becomes increasingly overestimated with more extreme hydrodynamic conditions.

These results indicate that the module may not be able to model saltmarsh vegetation effectively. The overestimation behaviour shown above suggests that the failure is due to the module and its foundational assumptions rather than an issue with the modelling presented herein. The problematic assumption might be the model used for the structure's behaviour, i.e., the geometrically exact Cosserat rod model, or the material the structure is assumed to be made of, i.e., Kelvin-Voigt linear viscoelastic material. To determine the root cause of the issue, this needs to be investigated further. Furthermore, this study is limited to investigating the force response of the flexible FSI module. The motion response of the structure is also output, which should be investigated. Continued exploration of the software's drag force response and motion response constitute the next steps in evaluating REEF3D's new flexible FSI module's efficacy for the modelling of saltmarsh vegetation. The current results also suggest that the theoretical underpinnings of the tool should be examined in more detail.

## CONCLUSIONS

This work tests the new flexible FSI module in the open-source CFD software REEF3D's applicability to saltmarsh vegetation under wave action in the greater context of NBS for coastal protection. Based on the physical modelling work of Paul et al. (2016), the module consistently overestimated the drag force response of plastic vegetation surrogates. While this suggests that this tool is unsuitable for this use, more work needs to be done before this can be stated with certainty. This will take the form of continued investigation into the drag force response of modelled flexible vegetation elements, exploration of the motion response, and further examination of the theoretical foundation of the FSI module.

## ACKNOWLEDGMENTS

This work was funded by the NRC Oceans Program (No. 138-1).

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