USING FLUID-STRUCTURE INTERACTION TO EVALUATE THE ENERGY DISSIPATION OF A TSUNAMI RUN-UP THROUGH IDEALIZED FLEXIBLE TREES

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Abstract. The extreme cost of massive concrete walls for the coastal protection from tsunamis is driving coastal communities around the world towards a paradigm switch in the design of their coastal stretches. Some regions of Indonesia and Chile, for example, are building coastal parks to mitigate the impact of a tsunami without drastically jeopardizing the livelihood of the coastal communities. Although these mitigation parks are becoming more and more popular, the hydrodynamics of the tsunami run-up through them has not been fully understood yet. Especially if the park is vegetated. In this study we use a fluid-structure interaction approach to estimate the amount of flow kinetic energy that is dissipated when the tsunami reaches shore and interacts with an idealized setting of rigid and flexible trees. This extended abstract presents an original small set of results from a larger scope work that is currently being drafted into a research article.

1 INTRODUCTION

Coastal communities around the world are increasingly incorporating nature-based elements such as coastal parks into their design of tsunami defenses as an alternative to off– and on–shore installed concrete walls. Coastal mitigation parks built on the shoreline are specifically designed to protect critical infrastructures and communities at risk behind the park. The protective benefits of mitigation parks have been recently studied in detail by [2] at large scale by means of a shallow water model designed for tsunami propagation in the open ocean. Once the tsunami reaches shore, however, the important turbulent and multi-phase nature of the flow as it moves inland is such that the shallow water model is no longer apt to describe the flow run-up. Furthermore, the tsunami runup is greatly affected by the structure of the boundary layer which cannot be possibly described by a shallow water model.

In this work we rely on the solution of a the Navier-Stokes equations describing turbulent free surface flows with explicit tracking of the free surface between the two fluids. Water and air interact by means a boundary forcing of the stress tensor at the water free surface. The free surface is tracked by the level-set formulation of [3] and citations therein. Turbulence is described by a large eddy simulation (LES) formulation of the Navier-Stokes equations. Given a computational grid, the flow properties (e.g. velocity, $\mathbf{u}$) are split into a grid-resolved quantity, $\overline{\mathbf{u}}$, and its unresolved part, $\mathbf{u}'$, according to $\mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}'$. For each fluid the following LES equations are solved by means of a finite element approximation in space and implicit time integration:

$$\begin{aligned} \frac{\partial \overline{\mathbf{u}}^i}{\partial t} + \nabla \cdot (\overline{\mathbf{u}}\,\overline{\mathbf{u}})^i &= -\nabla \overline{p}^i + (\nu + \nu_t)^i \nabla^2 \overline{\mathbf{u}} - \mathbf{g} & (1) \\ \nabla \cdot \overline{\mathbf{u}}^i &= 0 & (2) \end{aligned}$$

where $i = (\text{water}, \text{air})$, $\mathbf{g}$ is the acceleration of gravity, p is pressure, and ν and $\overline{\nu}_t$ are, respectively, the molecular and turbulence eddy viscosities. The eddy viscosity is calculated via the Vreman's sub-grid scale (SGS) model [4] on a smooth surface.

The fluid solver is coupled to a solid mechanics solver via the fluid-structure interaction (FSI) algorithm proposed by [1]. The coupling is achieved by means of a moving mesh via the Arbitrary Lagrangian Eulerian (ALE) formulation of the Navier-Stokes equations and adequate boundary conditions. The coupling is fully bi-directional; this means that not only the cylinders are deformed by the water[1], but the water is displaced by the moving cylinders in return.

To the authors' knowledge, this is the first time that fluid-structure interaction and large eddy simulation are used together to study free surface turbulent flows at large Froude and Reynolds numbers in the context of tsunami modeling. The first work where FSI was applied to flows with a free surface is also very recent and was proposed in 2016 by [5] to model the interaction of wind triggered ocean waves and off-shore floating structures in the context of wind energy.

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[1] The cylinders are modeled as fully three-dimensional elastic structures that can deform when subjected to external forces. The rigidity of each cylinder is imposed by a given value of its Young's modulus of elasticity

2 RESULTS

Circular base cylinders with diameter D were attached to the flat bottom surface of a closed three-dimensional box $\Omega = [0:15] \times [-2:2] \times [0:8]\,\mathrm{m}^3$.

We investigate two scenarios: (i) one cylinder centered at $(x, y) = (5 + D/2, 0)\,\mathrm{m}$ and (ii) two cylinders, mounted side-by-side, centered at $(x, y)_1 = (5 + D/2, 1/2 + D/2)\,\mathrm{m}$ and $(x, y)_2 = (5 + D/2, -1/2 - D/2)\,\mathrm{m}$. Each of (i) and (ii) was run twice: with $D = 0.5\,\mathrm{m}$ and $D = 1\,\mathrm{m}$. In the first round of numerical experiments, the cylinders were rigid (results not shown). In the second round, their structure was allowed to deform under the force exerted by the moving fluids. To quantify the effect of the diameter, configuration, and degree of flexibility of the cylinders on the flow energy dissipation, we calculated the energy flux across different surfaces along the flow direction up and downwind of the cylinders. Figure 1-left shows the water surface with two deforming cylinders. The right panel shows the time evolution of the kinetic energy flux across the yz-plane at $x_{P_3} = 8\,\mathrm{m}$. Unlike what we observed for the rigid counterpart of this same test (results not shown), the kinetic energy reduction with 1 cylinder is not affected by the cylinder diameter as much as it is for the case of two cylinders. In the case of rigid cylinders, the larger the diameter the more energy is either dissipated or reflected. Moreover, we observe that energy flux with one cylinder of $D = 1\,\mathrm{m}$ almost exactly overlaps with that of two cylinders of $D = 0.5\,\mathrm{m}$. The most energy dissipation or reflection appears to always be due to the presence of two large cylinders mounted side by side. We are currently working on a comprehensive analysis to map a full set of scenarios and draw the proper conclusions on the effect of cylinder size, configuration, and degree of flexibility.

3 CONCLUSIONS

We used a fluid-structure interaction solution to the Navier-Stokes equations for a turbulent free surface flow that interacts with a set of idealized rigid and flexible trees (cylinders). By means of a limited set of numerical experiments, it emerged that the cylinder configurations, diameter, and degree of flexibility are all consequential in the energy extracted (absorption and dissipation) from the water flow as it moves through the cylinders. This study is is the starting point towards a comprehensive analysis of the effect that coastal features and topography alike have on the hydrodynamics of a tsunami run-up in more realistic conditions at very large Reynolds and Froude numbers.

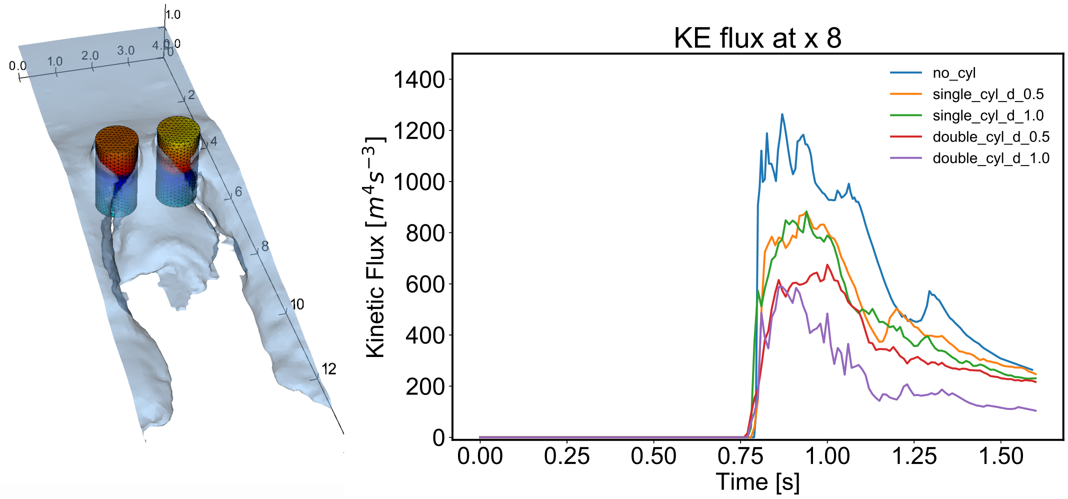

Figure 1: Left: snapshot of flexible cylinders displaced by the water. The cylinders are colored by maximum displacement, blue shading being the smallest and yellow the largest. Right: water kinetic energy flux across the yz plane at $x_{P_3} = 8\,\mathrm{m}$ for different cylinders and cylinder configurations. The reference flux is calculated without cylinders;

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