HIGH RESOLUTION NUMERICAL SIMULATION OF OSCILLATORY FLOW AND SEDIMENT TRANSPORT THROUGH AQUATIC VEGETATION

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EXECUTIVE SUMMARY

Aquatic vegetation provides a wide range of services to the ecosystem: improving water quality through nutrient uptake and oxygen production, providing flood buffering and coastal protection services, and regulating erosion and deposition patterns, thus playing a paramount role in habitat creation and promotion of biodiversity. While vegetation–flow interactions have been studied extensively for unidirectional flows, much less is known about oscillatory conditions. The current study is geared toward increasing our understanding of the interactions among vegetation, flow, and sediment under oscillatory flows. Direct Numerical Simulations (DNS) and Large-Eddy Simulations (LES) through different arrays of idealized vegetation, represented as cylinders, are conducted using the higher-order spectral element-based computational fluid dynamics (CFD) solver Nek5000. Different arrangements and numbers of cylinders have been simulated in 2D and 3D, with the largest simulation having ~296 million computational points, using up to 32,768 MPI ranks.

RESEARCH CHALLENGE

Seagrasses are commonly referred to as "ecosystem engineers" due to their ability to modify and stabilize their environments [1]. They are a fundamental component of near-shore ecosystems, providing a wide range of services [2] ranging from increasing water quality through nutrient uptake and oxygen production, creating habitats through spatial heterogeneity of the flow velocity, to dampening erosion on coastal wetlands. Past studies have focused mostly on unidirectional flows, relying strongly only on experimental approaches [3], with limited applications to oscillatory conditions. Such experiments provide ambient conditions closer to nature, although their measurements often lack the spatial and temporal resolution required to fathom the fundamental physical processes in detail. On the other hand, most numerical studies to date have primarily used CFD models based on temporal averaging of the Navier–Stokes equations, which approximate the turbulence in the system rather than accurately calculating it, and a few LES studies, which had to settle for a relatively small number of vegetation elements.

Our study is geared at bridging this gap by conducting numerical simulations at unprecedented scales, based on previous and ongoing experiments at the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign. We investigated flow through random and staggered arrays of cylinders to understand the effect of spatial heterogeneity of the vegetation on the flow. The study focuses primarily on oscillatory flow, though a few cases of unidirectional flow will be conducted for comparison purposes. Coupling the experimental and numerical study will yield further understanding of sediment dynamics under the influence of vegetation [4].

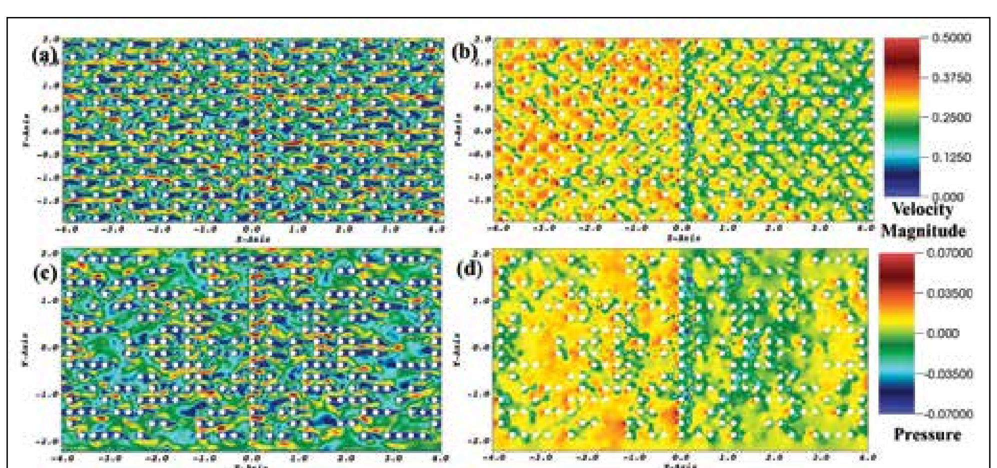

Figure 1: Instantaneous velocity magnitude (a,c) and hydrodynamic pressure (b,d) for oscillatory flow at Reynolds number ~10000. For staggered (a,b) and random (c,d) configuration of cylinders the flow has been captured while accelerating from left to right. For the staggered case, the vortex being shed from a cylinder is impeded by the ones behind it, which is not the case for the random case.

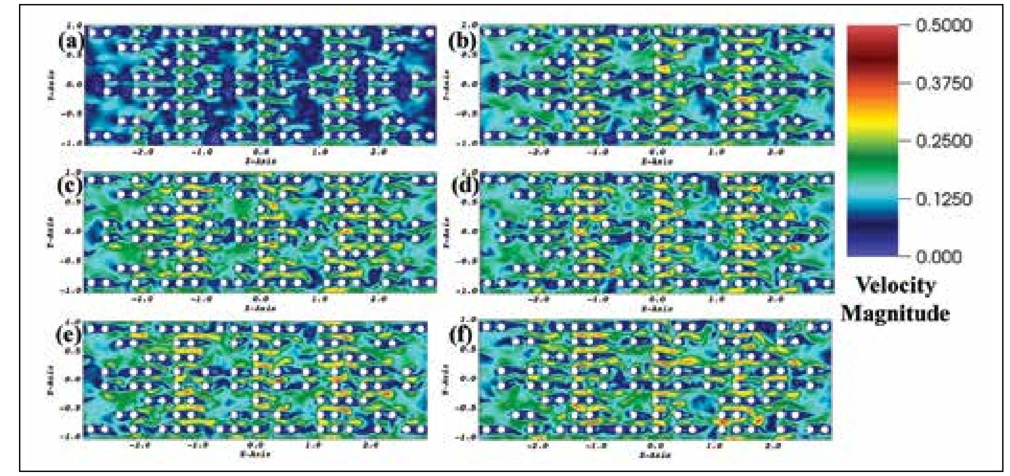

Figure 2: Results from 3D simulation of turbulent flow through a random arrangement of cylinders. About 296 million computational points are used. Instantaneous velocity magnitude at different elevations. Planes at (a) 0.5 %, (b) 1 %, (c) 10 %, (d) 50 %, (e) 75 %, and (f) 95 % water depth.

The scale of the experimental setup to be modeled is a challenge. The number of computation points required to model the whole domain is near 1.2 billion. While such simulations are still tractable on a petascale platform like Blue Waters, the computational cost is high, resulting in a reduction of the number of cases one can run, thus constraining the insights a broader range of parameters could yield. To increase variable space, a wide range of conditions are first simulated in 2D for the whole domain (~4 million computational points) to get an overview of the effect of different parameters such as Reynolds number, vegetation density, period and amplitude of the oscillatory flow, and spatial heterogeneity. Once the effects of different parameters are well understood, 3D simulations will be conducted for partial domains, big enough to accurately capture the general dynamics, but within manageable computational costs.

A better understanding of vegetation–flow dynamics will not only advance fundamental knowledge of physical processes but also will guide design efforts for scour protection and artificial wetlands. Part of the study is to characterize drag coefficients of the vegetation array, improving accuracy of reduced-order models of flow through vegetation. The study will also identify the ideal quantity and locations to place instrumentation in experiments through large arrays of cylinders.

METHODS & CODES

High-resolution LES and DNS of the flow at different configurations of the idealized vegetation were conducted using the open-source, spectral element-based higher-order incompressible Navier–Stokes solver *Nek5000* [5]. The Spectral Element Method combines the accuracy of spectral methods and the flexibility of Finite Elements Method [7]. In the planned simulations with sediment transport, sediment would be modeled as Lagrangian particles using a novel semi-implicit time-stepping scheme developed to simulate polydisperse sediment accurately.

RESULTS & IMPACT

2D simulations have been conducted for the full domain on different configurations. Two cases having the same vegetation density and Reynolds number, but different array configurations, are presented here. The velocity magnitude, along with the pressure field, is shown in Fig. 1. For the staggered case, in contrast with the random array, a vortex being shed from a cylinder is impeded by the ones behind it. This is evident in the pressure plots, where more and larger low-pressure areas, indicating the low-pressure core of rotating vortices, appear in the random case. For comparison, the random configuration was subjected to unidirectional flow at the same Reynolds number. High-flow zones near the walls arise, resulting in stronger vortices being shed from near-wall cylinders. Compared with the oscillatory flow case, more high-speed regions are also found among cylinders in the unidirectional cases.

Results from 3D simulations of turbulent flow through a random arrangement of cylinders have also been conducted (Fig. 2). A quarter of the full domain was simulated, with ~296 million computational points. Fields of instantaneous velocity magnitude at different elevations show that the length of the vortex being shed increases with distance from the bottom. This simulation, one of the largest high-resolution eddy-resolved hydrodynamic simulations in this field, will provide as yet unseen details of the physical processes involved.

WHY BLUE WATERS

The study pushes the limit of the scale at which high-resolution simulations are used to study complex multi-phase flow in environmental fluid mechanics, requiring computational resources with sustained computing power at an unprecedented scale, such as Blue Waters. Simulations have been conducted for up to 296 million computational points, with the code scaling strongly up to 32,768 MPI ranks. Without access to petascale HPC like Blue Waters, completing the study within a realistic timeframe would be impossible. In addition, since visualization of a phenomenon is an effective way to understand and explain its mechanics, we will work with Blue Waters project staff to create animations of the phenomenon using data from the simulations.