HIGH-RESOLUTION MODELING OF TURBULENCE IN WAVE BOUNDARY LAYERS

Allocation: Illinois/300 Knh
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EXECUTIVE SUMMARY

Wave boundary layer flows play an important role in coastal engineering and coastal sediment transport. However, current state-of-the-art models fail to accurately predict the complex mechanics of the turbulence and momentum exchange between seabed and free-stream velocity under oceanic flow conditions. Recent experimental and numerical studies in our laboratory indicate the presence of a phase lag between the time instance when the maximum bed shear stress occurs with respect to the maximum free-stream velocity in transitional oscillatory boundary layer flows. However, the effect of different levels of bed roughness and porosity remains unknown. This work is the first computational effort to simulate the effect of bed roughness height and bed porosity on the maximum bed shear stress phase difference compared to the maximum free-stream velocity value. It also examined the effect of turbulent flow structures on the bed–turbulent flow interaction, the ensuing sediment transport, and the bottom morphodynamics.

RESEARCH CHALLENGE

Recent experimental and numerical studies from our laboratory suggest the presence of phase lag between the time instances when the maximum bed shear stress occurs with respect to the maximum free-stream velocity in transitional oscillatory boundary layer flows. However, the validity of the phase-lag findings with respect to real seabeds, where different levels of roughness and porosity may exist, remains unknown. It is likely that the turbulent spots, which are arrowhead-shaped turbulent flow structures associated with local bed shear stress peaks and strong turbulent bursting, cause a phase lag to exist in the case of rough seabeds as well.

This work is the first computational effort to simulate the effect of bed roughness height and bed porosity on the maximum bed shear stress phase difference compared to the maximum free-stream velocity value. In addition, it is the first numerical study to quantify the effect of the roughness regime on the turbulent characteristics and quadrant analysis under oscillatory flow conditions. It is also the first study of the turbulent flow over various bottoms with varying porosities in the case of oscillatory flow, and among the first studies that have examined the mixing layer and momentum exchange between the free-stream oscillatory flow and the pore-scale flow under unsteady flow conditions.

METHODS & CODES

Extensive experiments using advanced experimental techniques in the Large Oscillatory Water-Sediment Tunnel at the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign suggest the presence of a phase lag between the maximum bed shear stress and the maximum free-stream velocity in the case of a smooth flatbed [1]. This observation is extremely important for the field of environmental fluid mechanics and coastal sediment transport, as this study is the first one in the literature that supports that the maximum shear stress is lagging instead of leading the maximum free-stream velocity over the period of each oscillation. Nevertheless, due to the limitation of the applied pointwise experimental technique used in the experiments (Laser Doppler Velocimetry), it was not possible to explicitly associate the presence of the bed shear phase lag with the development of the three-dimensional turbulence structures of the oscillatory wave flow, usually referred to as turbulence coherent structures. While advanced measurement techniques have been developed over the years, there is still no other available measurement technique that can give adequately detailed information, both spatially and temporally, to estimate all the needed parameters for the three-dimensional turbulence structures under an oscillatory flow. Thus, turbulence in complex three-dimensional flows is characterized mainly numerically, using a combination of high-order numerical methods and highly scalable numerical codes with backing from accurate experimental observations from the lab.

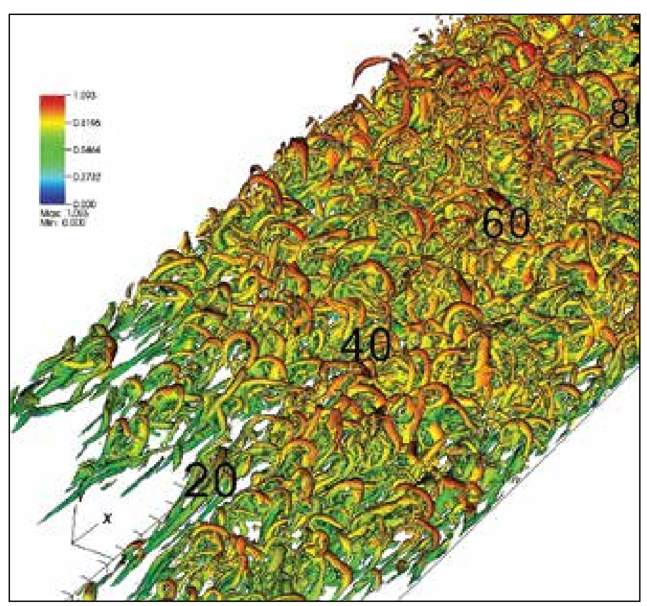

Figure 1: Turbulent flow structures (hairpin vortices) in oscillatory boundary layer flow (colored with the normalized velocity magnitude).

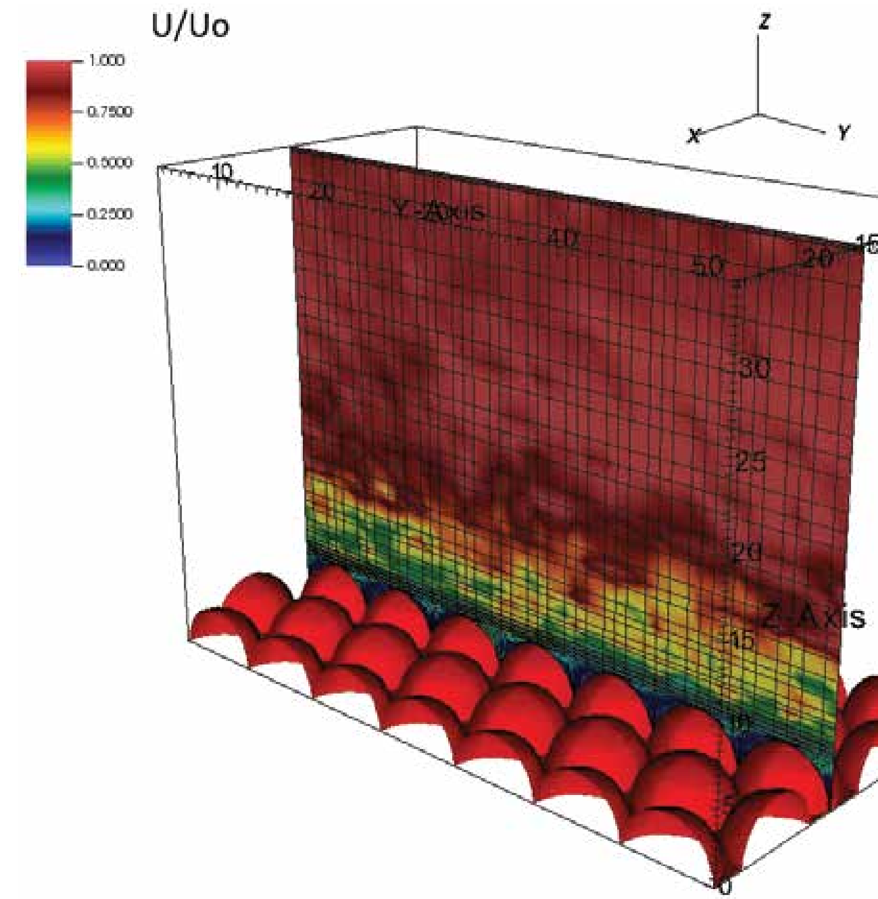

Figure 2: Flow-bed interaction in the case of oscillatory flow above hemispherical roughness elements.

We developed a Direct Numerical Simulation model capable of simulating the complex oscillatory boundary layer (OBL) flow and sediment transport using the Spectral Element Method (SEM) framework provided by the highly scalable open-source code Nek5000 [2]. Except for the analysis of turbulence characteristics of OBL flow over different bed conditions representative of the coastal bottom, the present work requires use of a proper model for the simulation of the suspended sediment using a Eulerian approach and proper boundary conditions for the sediment mass exchange between the coastal bed and the free-stream flow [3,4].

RESULTS & IMPACT

Our work is the first in the literature that explores the effect of turbulence characteristics of the flow and, particularly, the turbulent flow structures (Fig. 1) on the phase difference between maximum bed shear stress and free-stream velocity. It also explains the complex interaction between flow and bed for various bed characteristics (roughness and porosity: Fig. 2). It is expected that these previously unexplored physics related to the oceanic boundary layer and sediment transport will have a great impact on improving the accuracy of modern engineering tools and models used in everyday practice.

Our research will lead to a deeper understanding of the interaction of oscillatory turbulent flow, bed shear stress, and sediment mass transport, and eventually, will lead to the development of new, simplified but accurate models for the analysis and design of engineering systems in coastal and oceanic environments.

WHY BLUE WATERS

Such an analysis pushes the limits of turbulence-resolving numerical studies in terms of the computational resources and the high-performance computing facilities it requires and thus it can only be materialized on a petascale supercomputer such as Blue Waters. The work combines the expertise of Prof. Marcelo García's group from the Ven Te Chow Hydrosystems Laboratory of the Civil and Environmental Engineering Department at the University of Illinois at Urbana-Champaign and Prof. Paul Fischer's group from the Illinois Computer Science and Mechanical Engineering Departments with the leading-edge petascale computing resources of Blue Waters.