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DIRECT NUMERICAL SIMULATION OF TURBULENCE AND SEDIMENT TRANSPORT IN OSCILLATORY BOUNDARY LAYER FLOWS

Allocation: 300,000 Illinois/300 Knh
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EXECUTIVE SUMMARY

Oscillatory boundary layer flows play an important role on coastal and offshore engineering and the sediment transport mechanics in coastal environments. The present work will be the first computational effort to simulate the effects of turbulent structures and bed roughness on the maximum bed shear stress phase difference with respect to the maximum free-stream velocity and the first numerical study that will examine the mixing layer and momentum exchange between the pore-scale flow and the oscillatory free-stream flow for the case of turbulent oscillatory flow over porous bed. The proposed work combines the expertise of Prof. Marcelo García's group (Ven Te Chow Hydrosystems Laboratory, Civil and Environmental Engineering) and Prof. Paul Fischer's group (Computer Science and Mechanical Science & Engineering) with the leading-edge petascale computing resources of Blue Waters available at the University of Illinois at Urbana-Champaign and aims to become one of the most comprehensive studies on the effect of turbulent structures on the oscillatory boundary layer flows and sediment transport.

RESEARCH CHALLENGE

The growing human needs as well as global economic development have resulted in a rapid increase in marine activities. Coastal areas are usually involved in these activities in different ways, from hosting the foundation of offshore structures and breakwaters to accepting the residue of these activities in form of pollution or disturbance of the ecology and sediment transport. Numerical and theoretical models are being used by scientists, engineers, and decision-makers to design infrastructures and study the effect of marine activities on coastal environments and the sediment transport processes. However, most of the current state-of-the-art models fail to accurately predict the interaction of oscillatory flow with sediment transport, highlighting the existing knowledge gaps regarding the complex interactions between the oceanic flow, the coastal bottom, and sedimentation processes.

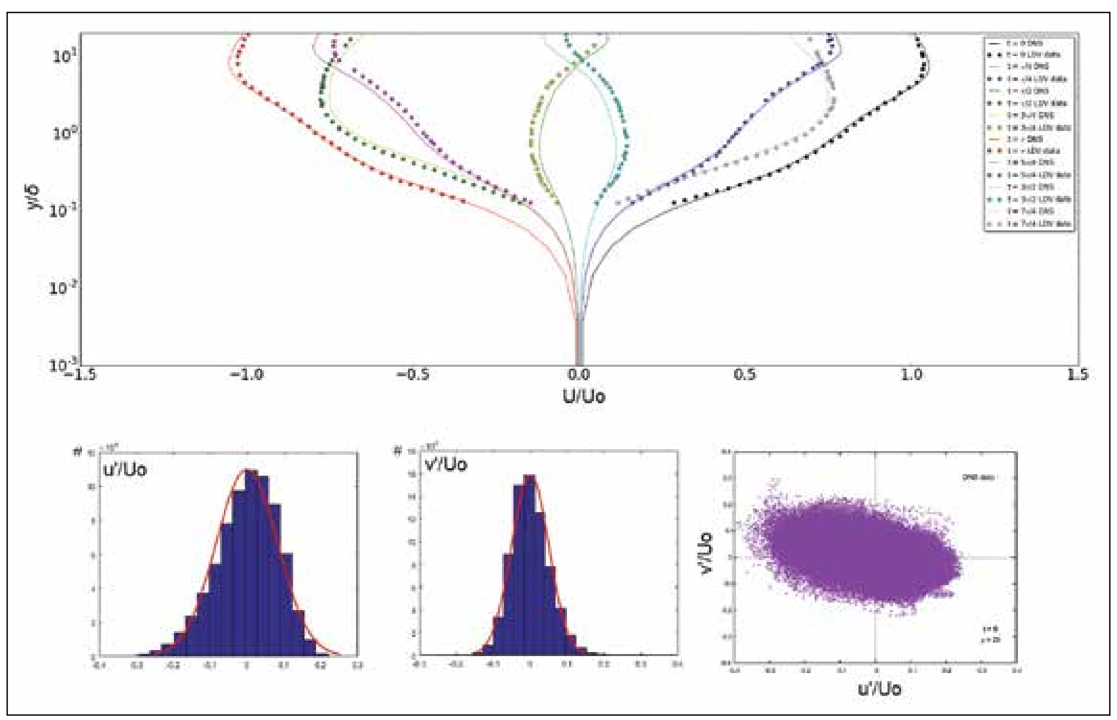

Figure 1A, B: Comparison between numerical results and experimental observations. Distribution and quadrant analysis of velocity fluctuations.

METHODS & CODES

Using advanced experimental techniques, extensive experiments have been conducted in the Large Oscillatory Water-Sediment Tunnel at the Ven Te Chow Hydrosystems Laboratory. These experiments 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 flat bed [1]. This observation is important for the field of environmental fluid mechanics and coastal sediment transport, as this study is the first one in the literature that supports the hypothesis 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. Thus, turbulence in complex three-dimensional flows is done mainly numerically using a combination of high-order numerical methods with backing from accurate experimental observations from the lab.

In the proposed work, we developed a Direct Numerical Simulation model capable of simulating the complex oscillatory boundary layer flow and sediment transport using the Spectral Element Method 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 an Eulerian approach and proper boundary conditions for the sediment mass exchange between the coastal bed and the free-stream flow (e.g., [3-4].)

RESULTS & IMPACT

Preliminary results show good agreement between the experimental observation [1] and numerical results for the case of the transitional/intermittent turbulent regime (Fig. 1A) [5]. Quadrant analysis of velocity fluctuations shows zones of sweeps and ejections (Fig. 1B) that dominate during the whole cycle of the oscillation. Also, velocity fluctuations seem to follow a normal distribution. These turbulence-related events (e.g., turbulent busting and associated ejections and sweeps) are known as mechanisms that interact with sediment particles [9].

Turbulence coherent structures (Fig. 2) are also examined for the case of oscillatory flow, confirming the presence of turbulence spots in the transitional regime of oscillatory boundary layer flows [6]. These lambda-shaped flow features are associated with local flow "bursts," causing local spikes in the local wall shear stress values [6]. These local flow structures are later developed, resulting in the onset of a more intense turbulent flow field close to the wall. The above are important findings for the field of sediment transport in coastal environments as bed shear stress is considered to be the main mechanism that is the major factor in sediment entrainment into suspension (e.g., [4]).

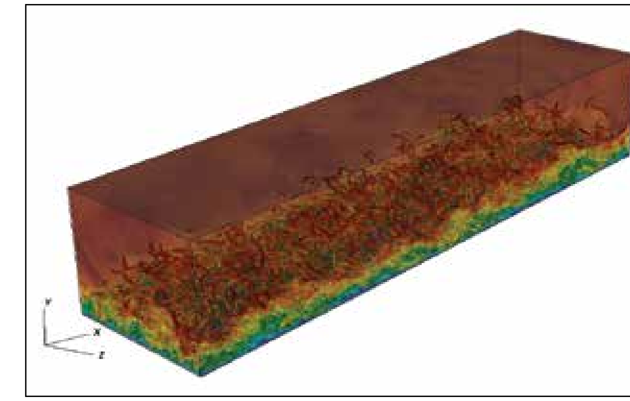

Figure 2: Turbulence flow coherent structures defined using the Lambda 2 criterion.

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

WHY BLUE WATERS

The present work pushes the limit of the turbulent-resolving flow modeling of oscillatory flows. The dimensions of the computational domain are chosen based on prior knowledge of experimental observation of "turbulent spots" [6–7] to ensure that the computational domain is big enough to allow these turbulent structures to develop. A sensitivity analysis has been conducted within the first quarter of the proposed project to ensure that the computational domain size is adequate for the formation of the coherent turbulent structures. The size of the used domain, which is larger than the previous studies' domains reported in the literature, together with the increased number of computational points (order 0.8 billion points), make the present work the first of its kind in terms of its turbulence/scale resolving results as well as its computational cost. The above, together with the requirement for the solution of several flow cycles to guarantee period-independent results, lead to increased computational requirements, making the use of a leading-edge petascale high-performance computing system like Blue Waters necessary for the success of the present work.