LARGE-EDDY SIMULATION OF SEDIMENT ENTRAINMENT OVER DUNES
A Singapore - Stanford Partnership proposal

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March 30, 2004

1. Overview

The objective of this project is to improve our understanding of particle entrainment in open-channel flows over a sediment bed with dunes. The study will be carried out through laboratory-scale experiments and well-resolved Large-Eddy Simulations [LES]. Specifically, we will investigate how the sediment pick-up rate varies over a dune and where the near-bed flow structures differ significantly from classical boundary layer or wake turbulence theory. With the analysis of experimental data, we hope to upgrade existing empirical sediment pickup formulae and then incorporate them into the numerical solver to provide well-resolved time- and spatially-variable descriptions of the three-dimensional velocity and sediment concentration fields, bed shear stress distribution, and sediment entrainment over the dunes.

The project will involve one Ph.D. student from NTU who will spend half of the project time working with the simulation code at Stanford University under Professor Street, who specializes in LES, and the rest of the time performing open-channel experiments and analyzing experimental and simulation data at NTU under Professor Cheng, who specializes in laboratory-scale experiments.

2. Background

In the presence of dunes, near-bed flow structures including distributions of turbulent velocities, bed shear stresses, and turbulence intensity are significantly modified (e.g. Zedler and Street 2001). Several experimental studies have also confirmed that the near-bed turbulence over much of the upslope of a dune differs markedly from either classical boundary layer or wake turbulence (Lyn et al. 2002).

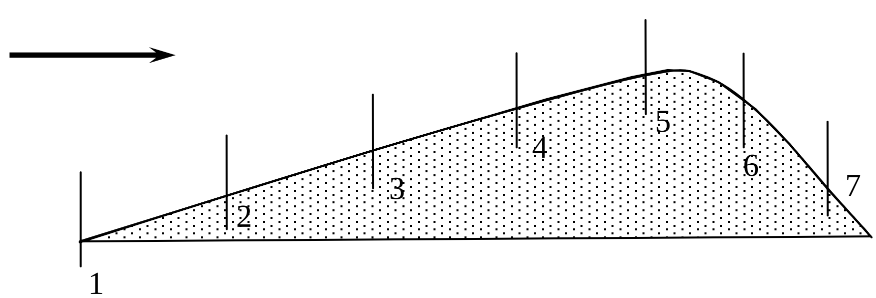
On the other hand, we note that current theoretical and empirical formulations of sediment transport such as pick-up functions are developed largely based on the classical boundary layer theory. How such formulations deviate from observations in the presence of dunes is not clear at the current stage. If the deviation is considerably large, the approach used for modeling transport rates over the upslope, which is based on the boundary layer shear stress distribution, would require substantial revisions.

In the Environmental Fluid Mechanics Laboratory (EFML) at Stanford University, a group directed by Prof Street is well experienced in LES of laboratory-scale environmental flows (see relevant publications included in References). For these simulations, the Boussinesq equations of motion are solved on a curvilinear coordinate nonstaggered grid. The equations are discretized in time using a fractional step approximate projection method and the pressure field is solved using the multigrid method. This method has been used along with a large-eddy simulation for subgrid and subfilter scale motions to study a host of three-dimensional flows. Examples include turbulent stratified flow over a wavy bed, the internal wave motions induced by a three-dimensional hill, the fundamental physics of breaking interfacial waves, and sediment transport over ripples.

In the hydraulics laboratory at NTU, facilities such as 3D-PIV and 2D-LDA are available to facilitate accurate measurements of turbulence in open channel flows. Prof. Cheng has been involved in conducting several analytical and experimental studies related to the effects of near-bed flows on sediment transport. Relevant research topics include probabilistic analyses of bed particle instability, the derivation of pick-up functions for sediment entrainment, the effects of turbulence on bedload transport, and the determination of critical condition for incipient sediment suspension. (See the References List for citations)

4. Proposed work

4.1 *Laboratory experiments.* A series of laboratory tests will be conducted to obtain spatial variations in pick-up rates of sediment particles at various locations over a typical dune. Both an isolated dune and closely-spaced dunes will be used for tests. Corresponding flow measurements will be also carried out either using 3D-PIV or 2D-LDA. Bed configurations will generally be comprised of isolated and closely spaced dunes, with smooth or particle-roughened surfaces. For example, consider a typical dune shape as sketched below. For each section (No.1 ~ No. 7), we are going to measure longitudinal and vertical velocities, pressure and sediment pickup rate. From the experimental studies, we are able to derive the essential parameters such as u_{mean}, v_{mean}, u_{rms}, v_{rms}, $-\overline{u'v'}$, p_{mean}, p_{rms}, and the pick-up rate over a dune.



4.2 *Large eddy simulations.* We propose to perform numerical simulations of the laboratory experiments, matching flow parameters and bedforms, with the Large Eddy Simulation code of Zedler and Street [2001]. These simulations will provide a three-dimensional and instantaneous description of the velocity and sediment concentration field, in which all of the fluid motions and eddies larger than a specified filter scale [usually twice the grid spacing] are resolved. While the experiments will provide the time-averaged bed shear stress distributions and pickup rates over the bedforms, the numerical simulations will provide an instantaneous description of both the bed shear stress distribution and boundary layer flow patterns. This pairing between numerical and laboratory 'experiments' will allow for various insightful investigations.

First, the numerical simulations can be used to compare the bedload sediment transport patterns and sediment pickup magnitudes as they vary over the bedforms in a time-averaged sense, for cases employing different classical and newly-derived [from the laboratory experiments] empirical pickup formulae. This would allow for comparisons of the predicted magnitudes of sediment pickup and the near bed transport patterns of sediment for the same flow field. Second, the simulations will provide instantaneous pickup rates and sediment concentration fields which can be used to analyze how the instantaneous bed shear stress distribution and near-bed flow field contribute to the time-averaged pickup rates measured by the lab experiments. Third, careful investigations of the velocity field structure induced by the dunes will allow for an improved understanding of the shear stress distribution, and its instantaneous fluctuation about the mean. It may also help to explain why sediment is picked up and entrained into the flow at one location, whereas it may be entrained and immediately deposited in another.

5. Schedule

The work would involve one Ph.D. student who would work towards the completion of his or her doctoral dissertation at Nanyang Technological University in Singapore, under the direction of Professor Cheng as the student's principal advisor, and Professor Street, the student's co-advisor.

• Year 1: Nanyang Technological University

- Take graduate courses.
- Review previous studies that are relevant to this project.

• Year 2 (9 months): Stanford University

- Learn how to use the numerical solver.
- Run simulations of laboratory-scale dune problems with existing sediment models.

• Year 2 (3 months) – Year 3: Nanyang Technological University

- Conduct laboratory experiments.
- Analyze experimental data and develop new pick-up functions for the condition of dunes.
- Incorporate the new functions into the numerical model.
- Compare simulations with laboratory measurements

- Year 4: Nanyang Technnological University
  - Run simulations of other laboratory-scale problems that are not easy to implement experimentally.
  - Analyze simulation results.
  - Write up dissertation.

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