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Bed particle entrainment and motion in turbulent open-channel flows: a high-resolution experimental study

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In spite of significant efforts of geoscientists and engineers, the exact mechanics of sediment entrainment and transport by turbulent flows remains unclear and continues to be the focus of many research groups worldwide. The talk outlines current developments in this direction at the University of Aberdeen, where an extensive experimental programme has recently been completed. The experiments were conducted in the Aberdeen Open Channel Facility (AOCF, 20 m long, 1.18 m wide) over wide ranges of flow submergence (1.9-8.0), bulk Reynolds number (4400-83000), and channel aspect ratio (9-39). The flume bed was covered by hexagonally-packed glass beads 16 mm in diameter. For entrainment experiments, selected glass particles were replaced with lighter particles (nylon and delrin). Instantaneous velocity fields before, during, and after entrainment were measured with an advanced multi-mode Particle Image Velocimetry (PIV) system developed by S. Cameron. This system was also used for 3D particle tracking in the entrainment experiments. The main types of experiments included: (1) multi-mode turbulence measurements with fixed-bed conditions to assess the background flow structure (10 min to 120 min duration of velocity records); (2) simultaneous measurements of fluctuating differential pressure acting on 23 fixed particles with in-built pressure sensors, synchronously with PIV; (3) measurements of waiting times for particle entrainment, employing a specially designed system (SMC-1) for automatic placement of the particles on the bed and subsequent measurement of the time before entrainment; (4) long-term direct measurements of the instantaneous drag force acting on a single particle (attached to the bed) at different protrusions, synchronously with PIV; and (5) synchronous measurements of the flow field around a particle before, at, and during entrainment, supplemented with 3D particle tracking. The key results include: (1) the refined turbulence structure of a rough-bed open-channel flow assessed with multiple-order bulk velocity statistics, spectra, correlations, and structure functions; (2) identification and quantification of coherent motions, with particular focus on 'superstructures' (or 'very large scale motions' up to 40 flow depths in length); (3) assessment of secondary current effects on the flow structure; (4) statistical characteristics of fluctuating pressure acting on multiple bed particles, including spatial pressure correlations and their relations to the coherent structures; (5) estimates and statistical tests of waiting time distributions; (6) statistics of particle trajectories with particular focus on the initial stages of motion; and (7) identification of typical flow features accompanying particle entrainment. Among other findings, it has been shown, for the first time, that particle entrainment is likely to be associated with interactions between flow superstructures. The 'collisions' of superstructures, 'meandering' across the flow, generate regions of a particular velocity pattern leading to the particle entrainment. This study was supported by an EPSRC (UK) Grant EP/G056404/1, which was directly linked to DFG (Germany) Grants FR 1593/5-1/2, focus of which was on direct numerical simulations of mobile-bed flows. The authors are grateful to M. Uhlmann and C. Chan-Braun (Karlsruhe Institute of Technology) and J. Frohlich and B. Vowinckel (Dresden Technical University) for their useful suggestions and insightful discussions throughout the course of this project.