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Kinematics of flow and sediment particles at entrainment and deposition

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A cohesionless granular bed subjected to a turbulent open-channel flow is analysed. The key objective is to clarify the kinematics of entrainment and deposition of individual sediment particles. In particular, we quantify a) the turbulent flow field in the vicinity of particles at the instants of their entrainment and of their deposition; b) the initial particle velocity and the particle velocity immediately before returning to rest.

The experimental work was performed at the Hydraulics Laboratory of IST-UL in a 12.5 m long, 0.405 m wide glass-walled flume recirculating water and sediment through independent circuits. The granular bed was a 4.0 m long and 2.5 cm deep reach filled with 5 mm diameter glass beads packed (with some vibration) to a void fraction of 0.356, typical of random packing. Upstream the mobile bed reach the bed was composed of glued particles to ensure the development of a boundary layer with the same roughness. Laboratory tests were run under conditions of weak beadload transport with Shields parameters in the range 0.007 to 0.03. Froude numbers ranged from 0.63 to 0.95 while boundary Reynolds numbers were in the range 130 to 300.

It was observed that the bed featured patches of regular arrangements: face centered cubic (fcc) or hexagonal close packing (hcp) blocks alternate with and body centered cubic (bcc) blocks. The resulting bed surface exhibits cleavage lines between blocks and there are spatial variations of bed elevation. The option for artificial sediment allowed for a simplified description of particle positioning at the instant of entrainment. In particular support and pivoting angles are found analytically. Skin friction angles were determind experimentally. The only relevant variables are exposure (defined as the ratio of the actual frontal projection of the exposed area to the area of a circle with 5 mm diameter) and protrusion (defined as the vertical distance between the apex of the particle and the mean local bed elevation).

Flow velocities were acquired with 2-component PIV and Vectrino-ADV. The former allowed for the spatial definition of the flow field around the particle with a temporal resolution of 15 Hz and the latter allowed for the collection of time series of 3 velocity components in the close vicinity of the particle with a temporal sampling rate of 50 Hz. High-speed video, with a sampling rate of 300 fps, was employed to register particle motion and Particle Tracking Velocimetry to retrieve material particle velocities.

Velocity measurements were grouped by categories of exposure and protrusion. The flow velocity in front of the particle, u_p, at the instant of entrainment are generally in accordance with a theoretical model

$$\frac{u_p^2}{(s-1)gd} = \frac{1}{C_D C_e C_0} \frac{\sin(\theta-\alpha)/\cos(\theta)}{1+\frac{C_L}{C_D}\tan(\theta)}$$

where $\theta-\alpha$ is the angle between the direction of the weight and the plane that encompasses the centre of mass of the particle and the pivoting axis, θ is the angle between the direction normal to the bed and the plane that encompasses the point of application of the hydrodynamic force and the pivoting axis, α is the angle between the plane of the bed and an horizontal plane, C_D and C_L are the drag and lift coefficients, C_e is the exposure coefficient, C_0 is an exposure correction, d is the diameter of the sphere, $s-1=1.53$ is the specific gravity of the spheres and g is the acceleration of gravity. It was also found that the flow velocities and the particle velocities at the instant of deposition were poorly correlated. Furthermore, preliminary results seem to indicate that the probability density function (pdf) of particle velocities just before returning to rest is similar to that of unconstrained moving particles.

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