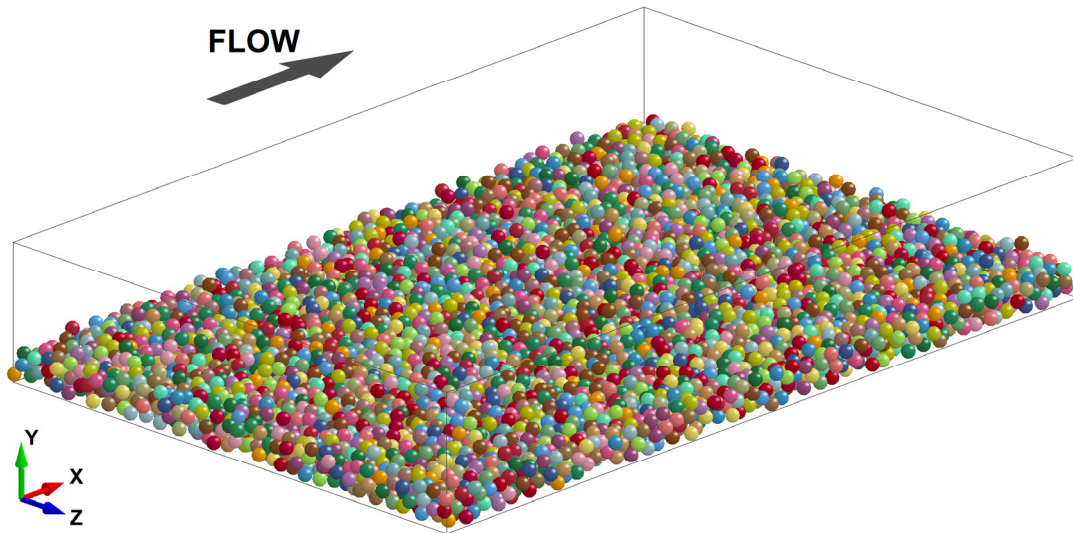
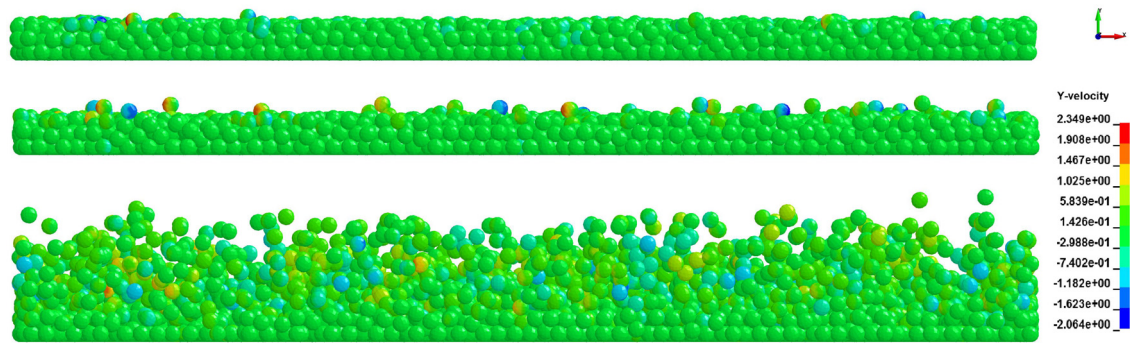


## Annex: Figures and Captions for the Project Report

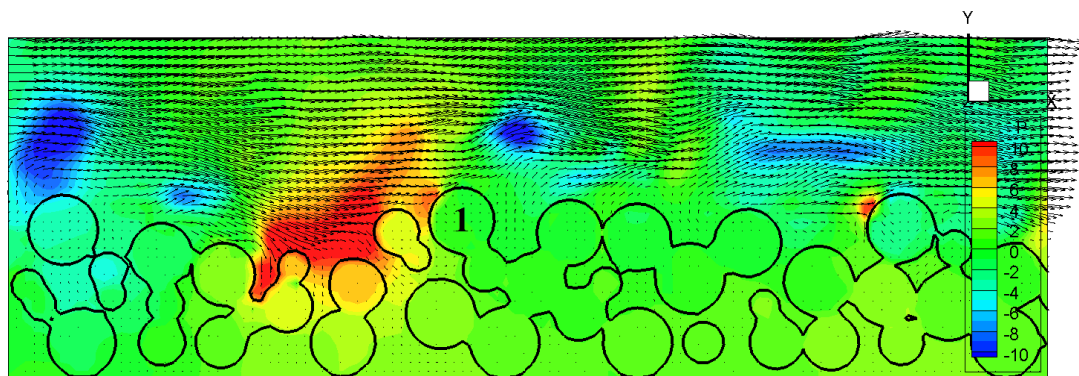
(Project Acronym: CFD-DEM)



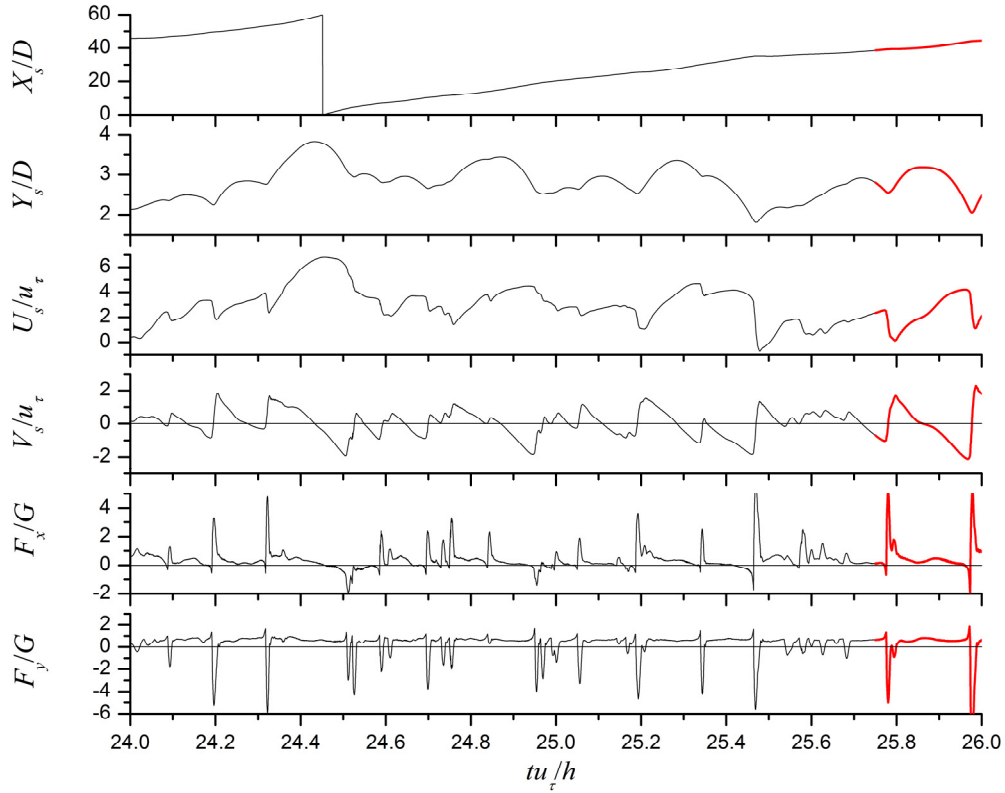
**Figure 1. Channel geometry and boundary conditions.** We consider the sediment transport in a fully developed turbulent open channel flow having a rough bed consisting of 2-3 layers of densely packed spheres. The size of the computational box is  $6d \times 4d \times d$  and the sphere diameter is  $0.1d$ , where  $d$  is the channel depth. The total number of spheres is 6355. No-slip boundary conditions have been used on both the bed and sphere surfaces. The top boundary is set as a free-slip hard lid. Periodicity is imposed in the stream-wise (X) and span-wise (Z) directions. The colour is used to indicate individual spheres.



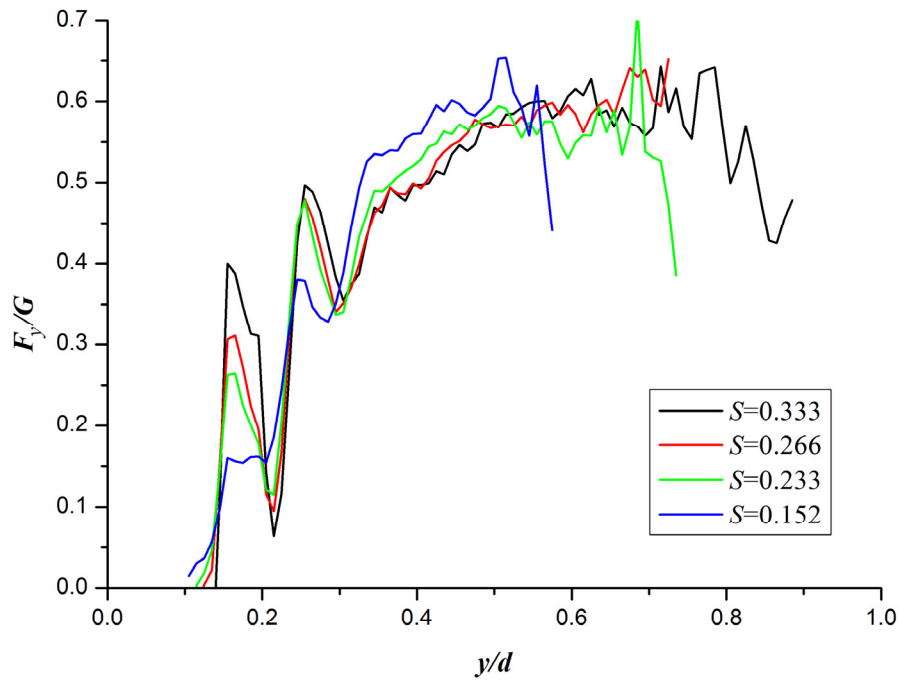
**Figure 2. Sediment entrainment in a turbulent channel flow with different Shield's Function values.** Three direct numerical simulations (DNS) with different values of the Shield's Function  $S$  show three distinctly different sediment entrainment patterns. When  $S=0.045$  (upper), just below the entrainment threshold of 0.055, particles are almost stationary. When  $S=0.065$  (middle), bed load is observed. When  $S=0.5$  (below), suspended load is observed.



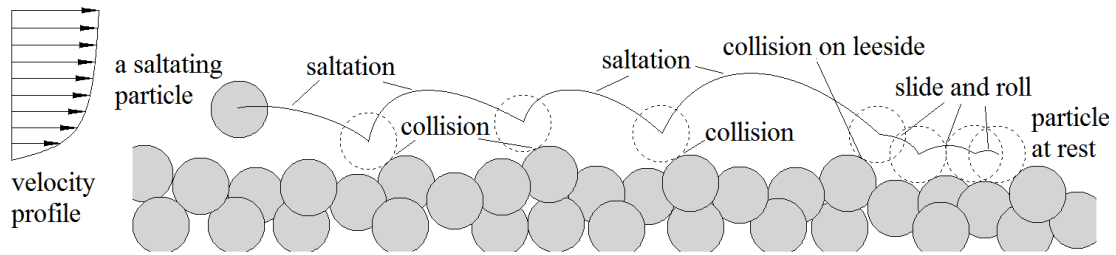
**Figure 3. A cross-section view of the flow fields at the inception of the entrainment of the target sphere (sphere 1) caused by sweep structures.** The colour indicates pressure. The vectors are plotted every two grids. The high pressure which expels the target sphere off the rough bed is caused by sweep structures.



**Figure 4. Dynamic responses of a particle during typical continuous particle saltations.**  $X_s$  and  $Y_s$  indicate the stream-wise and vertical coordinates of the particle, respectively,  $U_s$  and  $V_s$  represent the stream-wise and vertical velocities of the particle, respectively, and  $F_x$  and  $F_y$  are the drag and lift forces, respectively. Coordinates, velocities and forces are non-dimensionalized by particle diameter  $D$ , bed friction velocity  $u_\tau$  and submerged gravitational force of the particle  $G$ . Time is non-dimensionalized by  $h/u_\tau$ , where  $h$  is the effective depth of the channel. The jump in the stream-wise coordinate curve is due to the periodic boundary conditions in which particles moving out of the right boundary of the computational domain were artificially placed at the left boundary. The last saltation is indicated by thicker solid lines in red. It is observed that particles obtain vertical momentum mainly from their stream-wise momentum at collision, which can be deduced from the strong correlation between the abrupt decrease in the stream-wise velocity and the sudden increase in the vertical velocity.



**Figure 5. Normalized mean lift force on the particles versus the non-dimensional vertical coordinate.** Four large eddy simulations (LES) with different values of the Shield's Function  $S$  show similar results on the normalized mean lift force on the particles. It should be noted that the particle transport patterns in these simulations are in different regimes, i.e., the bed-load regime ( $S = 0.152$ ), the suspended-load regime ( $S = 0.333$ ) and a regime with both bed-load and suspended-load ( $S = 0.233$  and  $0.266$ ).  $F_y$  is the lift force on the particles,  $G$  is the submerged gravitational force of the particles,  $y$  is the vertical coordinate,  $d$  is the channel depth.



**Figure 6. Schematic diagram of the saltion mechanisms of large grain-size particles.** The mechanisms for the entrainment and the subsequent continuous saltation of large grain-size particles are different. Turbulence coherent structures, especially sweep structures, play a significant role in the sediment entrainment. Large particles are expelled off the rough bed by the pressure gradient generated by turbulence structures, as shown in Figure 3. However, for the subsequent continuous saltation, the collision parameters, such as incident angle, local rough bed packing arrangement, particle shape, particle density, Young’s modulus of particle materials, fluid viscosity, etc., are crucial. As shown in Figure 4, the gain in the upward momentum of a saltating particle is obtained from the loss of its stream-wise momentum at collision. So if there is not a significant collision between the particle and the rough bed, for example the particle hit the top leeside of a rough bed particle, the particle cannot obtain enough upward momentum to rebound from the rough bed and tends to slide on or roll over the bed particles. Because the particle cannot obtain enough stream-wise momentum due to the lower flow velocity in the vicinity of the bed, it will finally settle down. This particle will keep stationary until be entrained by a strong passing-by turbulence structure.