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Original Research

Laboratory measurements of vortex-induced sediment pickup rates

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ABSTRACT

In the present study, vortices were generated in open channel flow with a cross-flow cylinder installed horizontally near the bed. Sediment pickup rates were then measured over the channel bed downstream the cylinder using a sediment lift. The experimental data show that the pickup rate increases exponentially in the presence of vortices. Two different relationships can be clearly observed between the pickup rate and the maximum root-mean-square (rms) value of the streamwise velocity fluctuation, one for the cylinder-obstructed flow and the other for the unobstructed flow. The results imply that the vortex-induced sediment pickup cannot be explained based on the traditional boundary layer theory.

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1. Introduction

Vortices form when flow passes around a bluff structure. They can move with the flow, distorting by themselves and interacting with each other. Vortices have been a subject of interest to engineers and scientists for decades, but they are complex and an understanding of their mechanism still remains a challenging task. For example, vortices in a cylinder wake may involve interactions with a boundary layer, a separating free shear layer and a wake (Williamson, 1996). A moving vortex carries itself some momentum and energy. When approaching a sediment bed, a vortex could modify significantly near-bed flow properties and thus sediment pickup rates.

Cheng et al.'s (2003) measurements show that downstream a cross-flow cylinder, the fluctuation in the bed shear stress increases significantly, up to 102% of the mean bed shear stress, which appears closely associated with the vortex shedding. Sumer et al. (2003) observed that in the wake of a cross-flow cylinder, the local bedload transport rate could be 50 times higher than that induced by the same mean bed shear stress in a uniform open channel flow. Hopfinger et al. (2004) presented experimental results on sediment erosion by a plane wall jet, showing that sediment transport is primarily affected by streamwise vortices that create sediment streaks or ridges.

In the present study, sediment pickup experiments were conducted in open channel flows obstructed by a cross-flow cylinder, which was installed horizontally near the channel bed. The simple experimental setup, similar to that reported by Cheng et al. (2003), was able to generate vortices that enhance near-bed turbulence and thus sediment entrainment. Both flow velocity and sediment pickup rate were measured at several sections downstream the cylinder for the obstructed flow and also for the unobstructed flow (without any installation of cylinder). The results show that in the presence of vortex, the local pickup rate increases with increasing turbulence intensity, but following a trend different from that for the unobstructed flow.

2. Experimental setup

Experiments were conducted in a tilting flume (14 m long, 0.6 m wide and 0.6 m deep) with glass walls and a steel bed. The flume was equipped with a sediment lift, similar to that used by van Rijn (1984), which was attached to the channel bottom through a rectangular opening, 1.5 cm in the streamwise direction and 10 cm in the lateral direction, and installed at the section 9 m from the flume entrance (Fig. 1). Sediment particles were lifted up through the bed opening with a piston driven by an electrical motor. The piston speed and therefore the sediment supply rate can be adjusted by a control box. In addition, using a gear box, the piston speed could be reduced to 0.2 mm/min to facilitate low pickup rate measurements.

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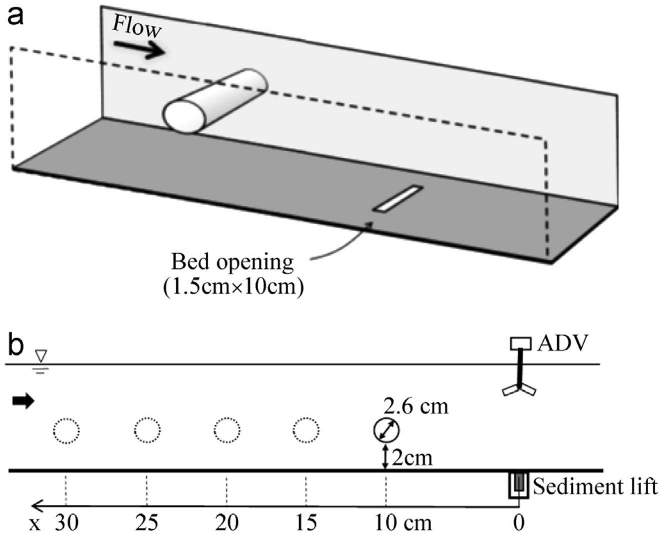

Fig. 1. Experimental setup: (a) 3D sketch; and (b) side view (not to scale).

The volumetric pickup rate E was measured as $V_T(1-\varepsilon)/(AT)$, where A is the area of the bed opening, T is the time duration for pickup measurement, and V_T is the bulk volume of the entrained sediment calculated as the product of A and the piston displacement measured by the dial gauge, and ε is the average bed porosity. Three uniform sediments of median diameter $D=0.23$, 0.44 and 0.86 mm were used, and the measured average porosity was 0.44, 0.43 and 0.40, respectively. The density of sediment grains $\rho_s=2650\ kg/m^3$. The critical shear velocity for the incipient sediment motion, which was calculated with the Shields diagram or Whitehouse et al. (2000) empirical formula, is equal to 0.013, 0.015 and 0.021 m/s, respectively. It should be mentioned that for each size of sediment tested, a layer of the same sediment particles was also glued onto the channel bed to ensure a consistent roughness throughout the channel.

Prior to each experiment, the flume was filled with water to a certain level and then the sediment lift was loaded with sediment particles to be tested. After the channel flow stabilized as desired, the piston speed was adjusted slowly so that only a single layer of moving particles was observed over and downstream the bed opening. At this stage, the piston displacement and the corresponding time duration were recorded.

During preliminary experiments, it was observed that there would be a pit over the observation area if sediment injection rate was smaller than the entrainment and a hump if injection rate was higher than the entrainment. The existence of a hump/hip would definitely affect the local flow field and thus the sediment entrainment. To minimize such uncertainties, the sampling time was taken long enough to cover several sequences of hump and pit occurrence. This resulted in an average measurement of the pickup rate for each particular test. To enhance the quality of the pickup measurement, the observation for each individual test was repeated at least five times to ensure that there was less than 15% difference among different measurements of pickup rates.

The observed pickup rate varied from 4.6×10^{-7} to 4.0×10^{-4} m/s. If the bed porosity is taken to be 0.42, the rate of change in the bed level can be calculated to be in the range of 1.1×10^{-6} to 9.5×10^{-4} m/s. In comparison, the measured near-bed flow velocity was more than 0.3 m/s. Therefore, the near-bed flow velocity was at least 300 times higher than the rate of change of the bed level. In addition, it is noted that the rms value of the velocity fluctuation in the streamwise direction varied from 0.034 to 0.175 m/s, which was at least 35 times higher than the rate of change of the bed level. Given the large differences, the effect of the change in the bed level on the near-bed flow field could be considered negligible.

To generate vortices, a horizontal cylinder (diameter=2.6 cm) was installed across the channel upstream the sediment lift, with a gap of 2 cm above the bed (Fig. 1). The gap chosen was found not to suppress the vortex shedding or to change its frequency (Sumer & Fredsøe, 2006). Different levels of turbulence were achieved at the test section by varying the distance from the cylinder location to the test section. By trial and error through a preliminary test, it was found that when the distance varied from $x=10$ cm to 30 cm (see Fig. 1), considerable variations were observed in the flow turbulence but relatively small in the mean flow velocity.

All measurements were carried out by setting the flow depth H at 20 cm and the bed slope at 0.0005. Four different flow rates were applied for each size of sediment. For each series of experiments with a fixed flow rate, flow velocity and pickup rate were measured under both obstructed and unobstructed flow conditions. For the obstructed flows, with the cylinder installed upstream the test section, five tests were completed with five different x-values (i.e. $x=10$, 15, 20, 25 and 30 cm). An additional test with the same flow rate was also conducted for the unobstructed flow, i.e. without any installation of cylinder. This may represent an equivalent case with a large x-value, for which the cylinder appears far away from the test section so that the vortex effect is negligible.

Flow velocity measurements were carried out using a three-component down-looking Acoustic Doppler Velocimeter (ADV). The ADV was positioned at the flume centerline right above the sediment lift and velocity measurements were completed prior to or after the pickup measurements. When conducting flow velocity measurements at the test section, the bed opening where the sediment lift was installed was covered, and its surface level was flush with the surrounding fixed bed. Therefore, the mobile bed over the bed opening had no effect on the flow measurements. For each velocity profile, 23–25 points were sampled at a rate of 50 Hz for three minutes. The shear velocity u_* for the unobstructed flow was estimated by fitting the logarithmic law to the velocity profile measured in the near-bed zone about 25% of the flow depth. Further information related to the experimental setup is given in Emadzadeh (2014).

3. Results

In total 72 experiments were completed and the data are summarised in Table 1. Fig. 2 shows an example of the profiles of the streamwise mean flow velocity u for the cross-sectional average velocity $U=0.59$ m/s and the sediment median diameter $D=0.23$ mm. Though being different from the velocity profile for the unobstructed flow, the five velocity profiles downstream the cylinder are very close to each other. The small difference in the cylinder-affected velocity profiles can be explained by the relatively small cylinder size compared to the flow depth and also the small streamwise reach ($x=10$–30 cm) which covered the selected cylinder locations.

Figs. 3–5 shows the profiles of u_{rms}, v_{rms} and w_{rms}, which denote the root-mean-square (rms) values of the velocity fluctuation in the streamwise, lateral and vertical direction, respectively, for $U=0.59$ m/s and $D=0.23$ mm. Being different from the small variations among the mean velocity profiles, the level of turbulence downstream the cylinder varied significantly. For example, the maximum value of u_{rms} increased from 5.9 cm/s for the unobstructed flow to 10.5 cm/s (about 1.8 times higher) for the obstructed flow with the cylinder at $x=30$ cm, and 17.2 cm/s (about 2.9 times higher) with the cylinder at $x=10$ cm. Similar variations can be observed in the maximum values of v_{rms} and

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