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Probabilistic description of coarse particle motion above threshold by particle tracking velocimetry method in an experimental study

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ABSTRACT: Sediment motion behavior plays an essential role in sediment and hydraulic engineering, though its physics is still not fully understood. Ignoring the stochastic nature of the sediment transport leads to various equations for bedload transport which are now being challenged due to their results. In this study, the non-suspended particle motion (bedload transport) in different hydraulic conditions was assessed by a particle tracking technique called Particle Tracking Velocimetry (PTV). The results of the PTV were applied to describe the particle behavior throughout the probability distribution functions. Knowing the particle motion behavior would guide learning more about the parameter/s governing the particle transport in different sediment transport regimes. The instantaneous particle velocity was measured after calibrating and validating the frames (resulted from the PTV). Different probability distribution functions were assessed with the Kolmogorov-Smirnov criterion (in 5 percent of the level of confidence) to find the best function which fits the collected data (i.e., the particle velocity). Furthermore, an analysis of the governing parameter for particle entrainment in different transport regimes was conducted. It was found that in a weak transport regime, the particle-bed and higher transport regime, the particle-flow interrelations were the governing factors that make the particle move. It was shown that the probability distribution function is Lognormal for lower particle Reynolds number, and on the other hand, in the higher particle Reynolds number, the Normal distribution best describes the particle velocity. The results of this research also could be applied in similar hydraulic conditions in the eco-hydraulic field, specifically macro-plastic movement as bedload in river courses and Aeolian research.

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1- Introduction

Coarse particle motion throughout the river courses or any open channel ducts near the bed could be in the form of saltation, sliding and/or rolling (i.e., bedload transport modes). Despite various research in bedload transport, the stochastic nature of the particle motion led to ambiguity and inapplicable equations for different hydraulic conditions [1,2]NiannianauthorauthorSingh,ArvindauthorauthorGuala, MicheleauthorauthorFoufoula-Georgiou,EfiauthorauthorWu, BaoshengauthorauthorscontributorstitlestitleExploringa semimechanistic episodic Langevin model for bed load transport: Emergence of normal and anomalous advection and diffusion regimestitlesecondary-titleWater Resources Researchsecondary-titletitlesperiodicalfull-titleWater Resources Researchfull-titleperiodicalpages2789-2801page svolume52volumenumber4numberdatesyear2016yeardates isbn1944-7973isbnurlsurlsrecordCiteEndNoteThe classical framework is based on the excessive bottom shear stress parameter, which initiates the bedload motion. The study of du Boys (reviewed in [3]) was the benchmark study for further research, which assumed the mean shear stress as the sole parameter responsible for the incipient and transport of the bed particles. Einstein ([4]) made the pioneering attempt on the probabilistic aspect of bedload sediment transport. He tended to describe the bed particle motion as fluctuating streamwise steps and resting intervals governed by the stochastic nature of the near-bed water velocity. Instead of using a single representative value of shear stress, Einstein related the number of particle grains in motion to the probability of the particle lift. Afterward, several researchers have proposed and adapted the stochastic framework for studying bedload transport (e.g., Grass [5], Sutherland [6], Ancey et al. [7]). A new interest among researchers arose after improvements in the high-resolution experimental and

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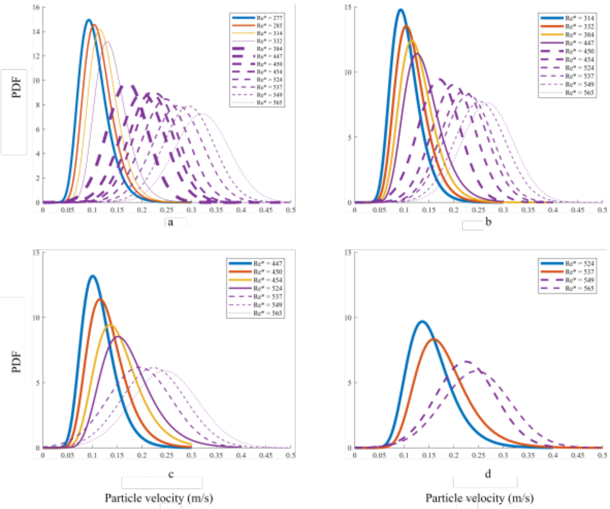

Fig. 1.Lognormal and Normal probability distribution functions in each experiment sets for four roughness a) ρ1, b) ρ2, c) ρ3 and d) ρ4

microscale monitoring techniques and improvements in statistical mechanics. Capturing images with a high-speed camera has enabled the Lagrangian measurement of sediment behavior in motion (Roseberry, et al. [8], Lajeunesse et al. [9] and Keshavarzi and Ball [10]). With image processing techniques, the particle trajectory could be monitored, and by employing a tracking method, the instantaneous motion parameters like velocity could be measured. Applying image processing techniques, which could be mentioned as particle tracking velocimetry (PTV), with stochastic models, there are several studies have been conducted to describe the bed particle motion (e.g., Ancey and Heyman [11], Fathel et al. [12] and [13]).

In this study, the application of the PTV has been conducted to monitor and explore the particle motion's behavior by capturing the particle's instantaneous velocity in transport. Information derived from the PTV permit drawing some conclusions on the physics of bedload transport by applying the best-fitted PDF, which describes the particle velocity. Different experiments with a specific range of flow rates and particle densities allow us to observe the PDF transitions for different bedload transport regimes.

2- Methodology

The experiments were conducted in the Water Engineering Lab at the University of Glasgow on a 1000×40×90 cm^3 (length, height and width, respectively) tilting flume over a test section of 150 cm length. Thirteen flow rates near and above the threshold of bed particle motion, delivered by a pipe with 14.2 inches size, have been tested. A bed made of well-packed beads has been set up over the test section to avoid dislodging during the experiments. Particle motion is captured by a high-speed commercial camera (GoPro with 60 fps and 1920×1080 pixel resolution), recording the top view covering the entire length of the flume bed. Particles with four different densities (ρ_1= 1380, ρ_2= 1501, ρ_3= 1620 and ρ_4= 2000 kg/m^3) are initially located at the upstream end of the configuration, fully exposed to the instream flow. The experiment parameters (e.g., flow rates, particle densities) were selected to cover the above near-threshold conditions, a low transport regime. Applying particle tracking velocimetry (PTV), the location and the instantaneous streamwise velocities of the exposed particle were derived. After calibrating and validating the frames, the center of the particle mass in each frame is identified so that its trajectory comprising consecutive displacements would accurately be defined. The PTV process was undertaken by an algorithm written in the MatLab environment. As bedload motion has stochastic nature, a probabilistic analytical approach is sensible to follow. By using the particle velocity measured from the PTV, different types of empirical probability distribution functions (PDFs; i.e., Normal, Exponential, Gamma and Lognormal distribution function) were produced and assessed by statistical criteria, i.e., Kolmogorov-Smirnov, to find the PDF which could adequately describe the streamwise velocity statistics.

3- Results and Discussion

Applying different Probability distribution functions, results showed that for lower particle Reynolds number (near-threshold), the particle velocity behaves Lognormal and for the higher particle Reynolds number, the Normal (Gaussian) function best describes the particle velocity probability distribution. In Figure 2, the Lognormal and Normal probability distribution functions are shown for different particle densities and different particle Reynolds number. As in prior studies (e.g., [14] and [15]), Lognormal was found to be capable of describing the instantaneous bed shear stress, it could be inferred that the bed particle transport in lower particles Reynolds number depend more on the particle-bed interactions and for higher particle Reynolds number which the transport regime is in an equilibrium state and the viscosity effects are getting weak, a Normal distribution is sensible to follow

4- Conclusions

The bottom (or bed) Shear stress, which was responsible for particle transport in the classical view, is only a crude measure of conditions contributing to the bedload motion physics. It is a quantity that is averaged over time and some specified spatial scale and contains very little information about the forces producing particle motions. Mean and fluctuating fluid forces are almost certainly involved in particle motions via local drag, and lift. However, particle-bed interactions are equally important. The form of the particle velocity distribution depends on the frequency with which particles interact with the bed in contribution to the fluctuating fluid forces acting on them. It was shown that in a weak transport regime (near-threshold), the particle velocity follows Lognormal distribution and for the higher transport rates, the particle velocity follows a Normal (Gaussian) probability distribution function as particles experience longer duration fluid forces and equilibrium in transport is satisfied.

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