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Velocity lag between particle and liquid in sediment-laden open channel turbulent flow

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HIGHLIGHTS

- Model on velocity lag between liquid and particle in open channel flow is derived.
- Hindered drag force and impact, viscous and turbulent shear stresses are included.
- Effects of particle–particle and particle–liquid interactions are considered.
- The suggested model is validated with a wide range of existing experimental data.
- The proposed model provides better result in comparison to other existing models.

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ABSTRACT

This study focuses on the prediction of velocity lag between particle and liquid in sediment-laden open channel turbulent flow. From theoretical point of view, we formulate a mathematical model of velocity lag based on hindered drag force on particle, impact shear stress, viscous shear stress and turbulent shear stress which are derived from the viewpoint of turbulence, particle–liquid interaction, particle–particle interaction and random dispersion of suspended sediment owing to these interactions. No estimation of empirical parameter is required for calculating velocity lag from the resultant model. The profile of velocity lag obtained is a function of particle diameter, mass density of sediment particle, shear velocity and vertical height from channel bed. The model also explains real phenomenological characteristics of velocity lag caused by the interaction between particle and liquid during turbulent flow. Our model well agrees with a wide range of twenty-two experimental runs collected from published literature. In addition, error analysis proves the superior prediction accuracy of our model in comparison to other existing models of velocity lag.

1. Introduction

Understanding the interaction between particle and liquid in sediment-laden open channel turbulent flow is one of the key issues in river geomorphological studies due to its impact on erosion and sedimentation. Traditional approaches did not take into account the complex mechanism involved in sediment transport and the two phases of particle and liquid are assumed as a sediment–liquid mixture during transportation [1–4]. By the advent of several advanced measurement techniques such as phase-Doppler anemometry (PDA), particle image velocimetry (PIV), particle tracking velocimetry (PTV), laser-Doppler anemometry (LDA), and discriminator laser-Doppler velocimetry (DLDV), separate measurement of particle and liquid velocities in sediment-laden flow has become possible and this advantage helps to understand the lag between particle and liquid phases for different turbulent features. Several experiments [5–14] have been done to predict the effect of different flow parameters on the lag of various turbulent quantities between liquid and particle phases. These experimental investigations reveal the velocity difference between particle and liquid phases and this difference contradicts the previous assumption [1–4] that sediment-laden flow can be considered as a simple mixture of particle and liquid.

Besides these experimental studies, literature [15–17] were based on the two-phase flow theory also discuss about velocity lag. Depending upon the concentration level of particles and

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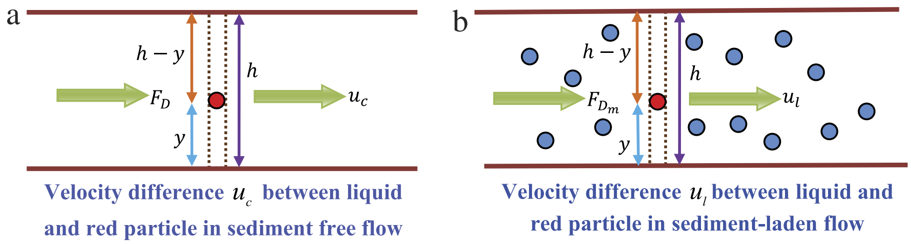

Fig. 1. Schematic diagram of (a) u_c and (b) u_l in flow region.

other physical properties in the flow, the governing equations of two-phase flow approach include one-way to four-way couplings which play significant role in the definition of particle's velocity [18,19]. Bombardelli and Jha [16] proposed hierarchy of two-phase flow models namely mixture model, partial two-phase flow model (PTFM) and complete two-phase flow model (CTFM) with increasing level of complexity in representing the flow through a set of equations. As the name indicates, implement of PTFM was made easier than CTFM by using the governing equations for mixture flow as surrogate for the fluid phase, thus reducing the complexity in numerical solution for solving mass and momentum equations of both phases. Our motivation for the present study stems from the fact that an analytical expression of streamwise velocity difference or velocity lag between liquid and particle in particle-laden flow would definitely reduce the complexity of PTFM by removing the need to calculate the velocity of particle.

Starting with two-phase flow theory, researchers analytically [20,21] or numerically [15] computed velocity lag and verified with limited experimental runs from published literature [5,8,12]. Chauchat and Guillou [15] did not consider the inter-particle collision and frictional effects of wall, though they mentioned the significance of these turbulent features in predicting velocity lag. It is worth mentioning that the calculation of velocity lag through two-phase flow approach encounters difficulty in rigorous numerical solution subjected to the estimation of various empirical parameters. Besides the two-phase flow theory, Cheng [22] predicted a mathematical model of velocity lag based on a hindered drag force in sediment-laden flow and stated that the model has limitations when particles receive intensive boundary collisions near the channel bed and significant gradients of velocity and concentration exist in the flow.

From the aforementioned discussions, we can infer that a generalized model of velocity lag in dilute and non-dilute sediment-laden flows can be developed by modifying the drag force together with the inclusion of interactive forces in suspension region during flow. This study endeavors to propose an analytical model of velocity lag which might be helpful to overcome the rigorous numerical calculation of velocity lag from two-phase flow approach. We organize the paper as follows. Section 2 describes the formulation of velocity lag model based on hindered drag force on particle in sediment-laden flow, impact shear stress, viscous shear stress and turbulent shear stress which take into account the effects of turbulence, particle–liquid interaction, particle–particle interaction and random dispersive nature of suspended sediment due to these interactions. Section 3 explains the selection of a wide range of experimental data to verify our model. Section 4 delineates the assessment of our model in predicting velocity lag. Through graphical representations and an error analysis, Section 5 presents a detailed comparative analysis between experimental data, our model and other published velocity lag models. Section 6 provides detailed discussions on the rationalization of real phenomena of velocity lag by our model and its excellency in comparison to other models from several aspects. The paper ends with brief conclusion.

2. Mathematical modeling

We start the mathematical modeling in deriving a hindered drag force acting on a suspended particle in sediment-laden open channel turbulent flow. Next, we derive the other forces acting on that particle due to the surrounding liquid and the intimate presence of other suspended particles. Based on these expressions of forces, we propose our velocity lag model.

In particle-free flow, the driving drag force F_D acting on a single suspended particle is expressed as

$$F_D = C_D \frac{\pi D^2}{4} \frac{\rho_f u_c^2}{2} \tag{1}$$

where u_c is the relative velocity or velocity difference between particle and liquid along streamwise direction, C_D is the drag coefficient, D is the particle diameter and ρ_f is the mass density of liquid. Keeping the same fluid flux for F_D and the drag force F_{D_m} in the presence of other particles in sediment-laden flow, Di Felice [23] connected them by a hindrance function H as

$$F_{D_m} = HF_D \tag{2}$$

Following Cheng [22], we write F_{D_m} by

$$F_{D_m} = C_{D_m} \frac{\pi D^2}{4} \frac{\rho_m {u_l}^2}{2} \tag{3}$$

where u_l is the streamwise relative velocity or velocity difference between particle and liquid in sediment-laden flow, C_{D_m} is the drag coefficient in that flow and ρ_m is the mass density of sediment–liquid mixture. The velocity differences u_c and u_l are shown by schematic diagrams in Fig. 1(a) and (b) respectively. We write H from Eqs. (1)–(3) as

$$H = \frac{C_{D_m}}{C_D} \frac{\rho_m}{\rho_f} \frac{u_l^2}{u_c^2}. \tag{4}$$

By assuming the particle distribution to be locally uniform in a prismatic volume of liquid containing randomly distributed particles and replacing the local concentration of particles by the volumetric particles' concentration c, Cheng [22] proposed a relation between u_l and u_c by

$$u_l = \frac{u_c}{1-c}. \tag{5}$$

The drag coefficient C_D generally depends on the particle Reynolds number Re given by

$$\mathrm{Re} = \frac{u_c D}{\nu_f} \tag{6}$$

where ν_f is the kinematic viscosity of clear liquid. It is observed that irrespective of flow nature, C_D satisfies two asymptotic relations which are $C_D = A_1/\mathrm{Re}$ for $\mathrm{Re} < 1$ and $C_D = A_2$ for $\mathrm{Re} > 10^5$ where A_1 and A_2 are constants. From these characteristics, Cheng [24] suggested C_D for the intermediate range of Re by

$$C_D = \left[\left(\frac{A_1}{\mathrm{Re}}\right)^{\frac{1}{n}} + A_2^{\frac{1}{n}}\right]^n \tag{7}$$