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Velocity profile of turbulent sediment-laden flows in open-channels

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ABSTRACT

In this paper, a study was carried out on the velocity profile of sediment-laden flows in open channels using a two-phase mixture model for two-phase flows. The governing equations for water-sediment mixtures were derived based on the two-fluid equations for solid–liquid two-phase flows. The drift velocity, a key variable involved in the two-phase mixture equations, was derived from the equation of momentum conservation for the solid phase. The drift velocity shows that the inertia of flow, particle turbulence, and collisions effect contribute to the dispersion of the sediment particles in turbulent flows. Using the two-phase mixture equation, the vertical velocity profile of open channel flows was obtained. Further analysis indicated that the distribution of the velocity over depth of water-sediment mixtures, composed of two different phases, is significantly affected by the turbulence of water-sediment mixtures and the density stratification. However, the velocity distribution is also affected by other factors including collisions between particles and particle turbulence as a basic feature of two-phase flows where interphase interactions inevitably mark their influence on the velocity distribution. Comparisons of this approach with observations for a wide range of experimental conditions are presented in this paper, which show that this approach agrees well with the experiments.

1. Introduction

Lying at the heart of boundary layer theory, the velocity profile has received considerable attention in the last ninety years. It has been confirmed that the velocity profile of incompressible, turbulent boundary layer flows is shaped by the diffusive momentum transport arising from the fluid viscosity and turbulence. When the flow of interest is laden with solid particles, their presence will inevitably affect the process of diffusive momentum transport in the boundary layer and in turn affect the velocity profiles. Studies on the velocity profile of sediment-laden flows have been the central topic of fluvial hydraulics over the last eighty years. However, there is still much room for further discussion, even on the most fundamental aspects. In this paper, the velocity profile of flowing water-sediment mixtures in open channels is discussed in the context of two-phase flows.

As a fundamental element in understanding fluvial processes in natural rivers and human-made canals, the velocity distribution of the water flow over depth has been studied extensively in the past decades. Although it has been a subject of persistent dispute, it is widely recognized that the velocity profile of a water-sediment mixture flowing in channels exhibits apparent differences comparing its counterpart for clear water flow except in the case of very low concentration (Vanoni, 1946; Einstein & Chien, 1955; Coleman, 1981, 1986; Wang & Qian, 1989; Umeyama, 1999; Guo & Julien, 2001; Cao et al., 2003; Wright & Parker, 2004a, 2004b). However, the key problem is how the presence of the sediment affects the velocity profile, which still remains an open issue and requires further investigation. Moreover, even on some basic points, for instance, whether the log law is applicable to describe the vertical velocity profile of sediment-laden flows is in question (Coleman, 1986; Guo & Julien, 2001; Wang et al., 2001).

The log law and the log-wake law are among the most frequently cited formulas used to describe the vertical velocity profile of wall-bounded shear flows in river hydraulics, with adjustable parameters of the von Karman coefficient (Vanoni, 1946; Einstein & Chien, 1955; Elata & Ippen, 1961; Wang et al., 2001), or the wake strength (Coleman, 1986), or both (Kereselidze & Kutavaia, 1995) calibrated with experiments to achieve better agreement between predictions and observations. In the early stages of the studies, the log law was first used to describe the velocity profile of sediment-laden flows and it was concluded that the logarithmic equation for clear water

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flows was in good agreement with experiments in the main flow zone but the von Karman parameter varies inversely with sediment concentration, while in the near wall zone, the velocity deviates from the logarithmic distribution due to density stratification (Vanoni, 1946; Einstein & Chien, 1955; Elata & Ippen, 1961; Wang et al., 2001). Coleman (1986) argued that the variation of the von Karman coefficient was largely the result of ignorance of the existence of a systematic deviation of the log law in the wake regions of wall-bounded shear flows. He further concluded that a logarithmic equation with a correction of adding a wake term is sufficient to give reasonable agreement between the theory and experimental results. He also reported that the wake strength previously introduced by Coles (1956) was affected by the presence of suspended sediment based on his own experiments. The conclusion obtained by Coleman (1986) about the wake strength was theoretically explained in a discussion by Parker and Coleman (1986), which showed that the wake strength corresponding to the presence of sediment is linearly proportional to the sediment concentration. However, with further study Julien and Lan (1988) found that the presence of sediments does not necessarily increase the wake strength coefficient. Although disputes about the variation of the wake strength with the concentration still exist, the log-wake law was accepted by many researchers and further steps were taken to study the velocity profile of flows of water-sediment mixtures in open channels. For instance, Kereselidze and Kutavaia (1995) reported that both the von Karman coefficient and the wake strength were correlated to the sediment concentration. Moreover, Guo and Julien (2001) showed that the log-wake law, even with both the von Karman coefficient and the wake strength adjusted, was insufficient to describe the velocity profile over depth of sediment-laden flows, and, thus, an additional term was added to the log-wake law. It should be noted that the power law for the velocity profile of flowing sediment-water mixtures is also popular in engineering practice because of its simplicity (Zheng et al., 2013), but it still suffers the limitations of the log law or the log-wake law when applied to flows with heavy sediment concentrations.

The log law and the log-wake law were borrowed directly from fluid dynamics for single-phase flows rather than being rigorously formulated theories for sediment-laden flows. This fact could be one reason largely responsible for the confusing conclusions about what makes the velocity profile over depth of sediment-laden flows different from their counterparts for clear water flows. In view of this fact, aimed to provide better understanding of the underlying principles based on much sounder physical grounds, many studies were conducted and theories were developed based on various considerations of the effect from the existence of sediment. For instance, Lyn (1988) put forward a similarity theory which examined the effect of the sediment on the velocity profile via introducing a length scale which was closely associated with the sediment motion. Kovacs (1998) proposed a modified Prandtl mixing length theory for sediment-laden flows, in which a damping function varying with local concentrations was applied to consider the influence of the sediment particles. The calculations of Kovacs (1998) showed that the mixing length of a water-sediment mixture is less than that of a clear water flow, which was partly confirmed by the experimental study Best et al. (1997). Cao et al. (2003) also suggested a model with the consideration of turbulence modulation found in wall-bounded, turbulent shear flows due to the presence of suspended sediment. In their studies, some parameters were proposed to represent interferences for the coupling of water and sediment particles on the turbulence. It is notable that these parameters were selected based on the conclusions drawn by many experimental investigations into the details of the turbulence modulation because of sediment particles. For example, rather than using the sediment concentration as the sole parameter accounting for the turbulence modulation caused by the coupling of the two-phase systems, the Stokes number of the particles and the ratio of particle size to the Taylor microscale of clear turbulent water flows were used as two indexes of the turbulence modulation. This approach accounted for the effect of the suspended sediment on the turbulent eddy viscosity. Different from the research focusing on microscopic influences from the alteration of turbulence because of the presence of sediment particles, McLean (1991), Villaret and Trowbridge (1991), Wright and Parker (2004a, 2004b), Herrmann and Madsen (2007), Pittaluga (2011), among many others, elucidated that the density stratification was another important factor which acts as a buoyant force affecting the vertical mixing of the eddies in water-sediment mixtures.

Although numerous studies regarding the velocity profile of water-sediment mixtures in open channels have been reported, further discussion is still needed. The most fundamental issue is whether the theories inherited from fluid dynamics and hydraulics for single-phase flows are applicable to sediment-laden flows, i.e. the typical solid/liquid two-phase systems. Although the sediment particles and fluids constitute mixtures which are transported as a whole in channels from a macroscopic point of view, the differences in terms of the velocities of each phase still exist, which can significantly alter the macroscopic characteristics of the flow composed of a water-sediment mixture. In the single-phase treatment of sediment-laden flows, the equations of mass, momentum, and energy conservation are derived under the assumption that the water and sediment are well-mixed, and thus, the mixtures composed of these two phases are regarded as pseudo-single phase fluids. This assumption helps to significantly reduce the complexity in developing theories and models for the purposes of engineering practices; however, this assumption conceals the interphase interactions in flows of water-sediment mixtures because the interactions are internal forces and are not present in the field equations for water-sediment mixtures, except that the density stratification effect is explicitly considered (Guo & Julien, 2001). Therefore, because there is a lack of proper theories for sediment-laden flows, a large portion of the previous studies can only apply the theories and approaches for single-phase flow to investigate the complicated phenomena observed in two-phase flows.

Theories developed for multiphase flows have been applied to study a variety of problems of interest in fluvial hydraulics (Drew, 1975; McTigue, 1981; Cao et al., 1995; Greimann et al., 1999; Wu & Wang, 2000; Greimann & Holly, 2001; Hsu et al., 2003, 2004; Liu & Singh, 2004; Fu et al., 2005; Jha & Bombardelli, 2008, 2010, 2011; Toorman, 2008; Chen et al. 2011; Zhong et al., 2011) and these theories show exciting potential in considering the complicated interphase interactions and their impacts on erosion, transport, and sedimentation of sediment particles. Two-fluid models for two-phase flows have attracted considerable interest from researchers of fluvial hydraulics because of the models' rigorous theoretical formulation. Most importantly, two-fluid models present themselves in the form of macro-conservation laws, which are familiar to researchers of fluvial hydraulics whose concerns are largely focused on the macro-features of flows such as the temporal and spatial variation of velocity, sediment concentration, and accompanying fluvial processes. For this reason, two-fluid models have been applied to studies of sediment-laden flows and satisfactory results have been obtained in various applications.

The models developed based on the completely well-mixed single-phase treatment of sediment-laden flows prevail in fluvial hydraulics. On the other hand, there are two main reasons which prevent further applications of the two-fluid model in fluvial hydraulics where much more complicated situations are encountered than in industrial counterpart problems. One of the reasons is the possible uncertainties involved in the closure of two-fluid models; the other is the relatively high cost in solving the governing equations of two-fluid models. In