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Research paper

# Large-eddy simulation of horizontally discharging sediment-laden jets

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**Abstract**

Horizontally discharging jets laden with sediment particles are investigated numerically. The computation of the fluid phase is conducted by Large Eddy Simulation (LES) while Lagrangian particle tracking is used to calculate the motion of sediment particles. Both momentum and buoyant discharge cases of sediment-laden jets are simulated. The computational results reveal that the advecting large eddies are responsible for the formation and the transport of high-concentration particle patches in the jet flows. For a horizontally discharging buoyant jet, it is observed that there exists a significant correlation of particle abundance and high turbulence intensity in the lower outer layer of the jet flow when its trajectory is deflected by buoyancy. The investigation of the instantaneous vorticity fields shows that the particle transport in horizontal sediment jets are large associated with the large eddies in the flow.


*Keywords:* Buoyant jet; Sediment particles; Multiphase flow; LES

## 1. Introduction

Sediment-laden jet is a type of multiphase particle-laden flow, in which the suspended solid particles have a density greater than the carrying fluid. It is often encountered in natural and engineering processes, such as volcano eruption, stack emission of waste gases and premixing of chemical reactors. A particular case of hydro-environmental concern is wastewater discharge via ocean outfalls, in which the heavier solid particles fall out of the flow and form a sludge bank in the region near to the discharge point, while the lighter particles may remain in the fluid for a longer time and be carried away to a wider area. Depending on the chemical and biological nature of the particles, both of these outcomes may affect the local ecology (Tchobanoglous and Burton, 1991).

Previous studies on sediment-laden jets mainly focused on the momentum jets, in which the jet effluent and the ambient fluid have the same density (e.g., Neves and Fernando, 1995; Carey et al., 1988; Bleninger et al., 2002; Lee, 2010). However, in many hydro-environmental problems, buoyancy often plays an important role and may complicate the behaviors of multiphase flows. A considerable amount of research effort was given to the simple case of a vertical particle-laden jet, which has a symmetrical mean flow with respect to the direction of the gravitational force (e.g., Neves and Fernando, 1995; Jiang et al., 2005; Hall et al., 2010). For ocean outfalls, wastewater is often discharged horizontally to achieve a maximum initial dilution. In this case, the resulting buoyancy from the density difference between the jet effluent and the ambient sea water leads to a deflected jet trajectory, which in turn may has great impact on the settling patterns of sediment particles within the discharging wastewater. Flow visualization results in the laboratory (Fig. 1) show that the distribution of the laden particles is highly non-uniform in the bending region of the buoyant jet with more particles present in the outer and lower part of the jet (Li, 2006). To our knowledge, relatively

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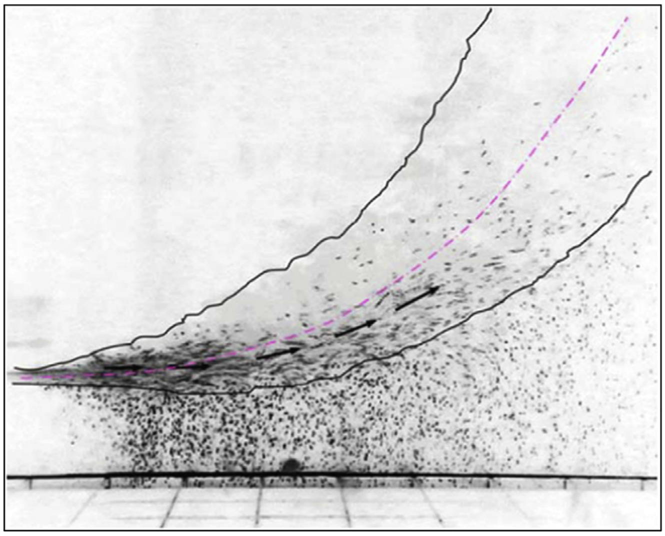

Fig. 1. Flow visualizations of sediment-laden buoyant jet, from Li (2006).

little work has been reported on this type of flow despites some exceptions including Lane-Serff and Moran (2005), Li (2006) and Cuthbertson and Davies (2008).

The global behaviors of a sediment-laden jet were the usual target in most past studies, either those of engineering concerns or theoretical modeling, whereas the local and instantaneous flow behaviors have largely been overlooked. In our recent experimental investigation of a horizontally issuing sediment-laden jet (Liu and Lam, 2013a), we observed that a large amount of sediment particles falling in the form of particle-concentrated "finger" structures from the main jet flow. Similar particle-concentrated structures have also been observed in the experimental studies on particles settling from the surface flow generated by a vertical particle-laden plume (Carey et al., 1988; Zarrebini and Cardoso, 2000). It was explained that these "finger" structures arise from the motion of dense particle-fluid mixture on a lighter fluid (Carey et al., 1988), which is related to Rayleigh-Taylor instability. The "finger" structure appears to be a universal form of falling behavior of heavy particles from a turbulent flow, but no further study was devoted to this interesting local phenomenon. An understanding of this phenomenon would inevitably contribute to the understanding of the jet global behaviors as well as properties of other types of particle-laden flows.

Both experimental and numerical investigations are necessary to obtain reliable information for a complex flow. However, some important flow quantities are difficult to be measured in a laboratory experiment. For the present case of particle-laden jets, the distribution of particles is crucial in understanding the flow but quantitative in-situ information of particle concentration is difficult to gather experimentally. Some measurement techniques for particle concentration nowadays are based on particle counting with image processing, but they have inherent arbitrariness and require ad-hoc calibration (e.g., Lee, 2010; Fessler et al., 1994). In this regard, numerical simulations have the advantage of producing extensive data for the whole flow field. In particular, the data of particle concentration can be readily obtained.

For the purpose of easy application, an engineering flow is usually modeled as steady or pseudo-steady and the characteristics of the mean flow are used as parameters. In particle-laden flows, however, the motions of the relatively small particles actually depend on the instantaneous velocities of the fluid flow. This is especially true for a turbulent jet, in which the magnitudes of instantaneous velocities can be several times greater than the mean value (Webster et al., 2001). Thus, models based on mean flow analysis may be difficult to predict the sediment-laden jets. On the other hand, large-eddy simulation (LES) may provide an opportunity for the numerical investigation of this type of flow, for the velocity fluctuations of the fluid phase can be resolved down to the sub-grid scale. The instantaneous velocities produced by LES could be used as inputs for a reliable calculation of the particle movements. Another benefit from LES is that it helps better reveal the local structures in a particle-laden jet flow.

This paper describes a series of numerical simulations of particle-laden jets, from the simple case of a momentum jet to the complex case of a horizontally discharging sediment-laden buoyant jet, by harnessing the instantaneous velocity fields produced by LES. The motions of the particles are calculated with a Lagrangian model. We target dilute sediment-laden jets, corresponding to flow conditions with low concentration of sediment particles. In this approach, the contact forces exerted on the particles can be calculated from the instantaneous fluid velocity. The simulations are thus like numerical "experiments", whose results are more realistic than those from numerical simulations based on mean flow modeling. Both fluid velocities and particle concentration in the whole field are obtained. We validate the LES modeling against well-accepted data of particle-free jets and verify the numerical method of particles initiation by the simulation of a vertical particle-laden jet. The local mechanisms of how the fluid flow carries sediment particles inside a horizontal jet are explored. Coherent structures of particles and fluid flow are also discussed.

## 2. Numerical modeling

### 2.1. LES of the fluid phase

The flow of a Newtonian fluid is described by the continuity equation and the momentum (Navier–Stokes) equation,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left( \rho \vec{u} \right) = 0, \tag{1}$$

$$\frac{\partial}{\partial t}\left( \rho \vec{u} \right) + \nabla \cdot \left( \rho \vec{u}\,\vec{u} \right) = -\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g}, \tag{2}$$

where $\vec{u}$ is the vector field of velocity, and the symbols $\rho$ and $p$ represent the density and pressure of the fluid in the flow field, respectively. The dynamic viscosity of the fluid $\mu$ is a constant. A spatial or temporal filtering (e.g., Reynolds averaging) of the momentum equation gives rise to the turbulent stresses $\rho u_i' u_j'$, where $u_i'$ is a component of the fluctuation velocity. The production of turbulent stress is believed to depend on the