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Software for evaluating sediment-induced stratification in open-channel flows

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ABSTRACT

Open channel flow containing sediment suspension subjects itself to a density gradient in the vertical direction, i.e. density self-stratification, due to the tendency for suspended sediment to settle. Velocity and concentration profiles under the effect of density stratification may differ significantly from the conventional logarithmic and Rousean distributions associated with open channel flow. It is hence important to include this effect into flow computations in order to accurately predict flow characteristics such as the resistance coefficient, near-bed sediment concentration, flow and sediment discharge. In this study we introduce a software, StratSedOC, for such purpose. The application contains a user-friendly interface which allows users to evaluate and visualize the differences in the velocity, concentration and eddy viscosity profiles when stratification effects are taken into account. In addition to the standard logarithmic/Rousean formulation, the model uses three turbulence closures, i.e. an algebraic model (Smith–McLean) and two differential models (k-ε and Mellor–Yamada). The software application can also be used to study the effect of sediment mixtures on flow stratification under different boundary conditions for near-bed sediment concentration. Comparison among the model and experimental results suggests that the Mellor–Yamada model predicts a damping effect on the eddy viscosity which is similar to the Smith–McLean model, while the k-ε model consistently predicts weaker stratification effects. Based on this result, a modified boundary condition for the k-ε model is then proposed.

1. Introduction

Sediment suspension in open channel flows induces flow stratification. The phenomenon differs from stratification in atmospheric or oceanic flows in that it is self-induced owing to the tendency of the particles carried by the flow to settle. The properties of the suspension, such as the grain size distribution and concentration, are thus keys to describing the level of stratification for this type of flow. Under the effect of sediment-induced stratification, flow characteristics including sediment transport rate, sediment concentration in the water body and resistance coefficient, as well as the resulting river morphodynamics, may change substantially. It is of interest to civil engineers and sedimentologists to understand and model the effect of self-stratification on open channel flows.

The main observed effect of self-stratification on the flow is an increase in the vertical gradient of the streamwise velocity, an effect that has been observed in various experiments (e.g. Einstein and Chien, 1955; Vanoni, 1946; Coleman, 1981, 1986). The explanation for this effect that has been most commonly embraced by modelers is based on an analogy to heat flows, according to which the buoyancy flux induced by density gradients extracts energy from the flow. This reduces the ability of flow to exchange momentum, and hence increases the flow velocity. In the case where complete damping of turbulence occurs, the flow loses the ability to sustain sediment, resulting in 'catastrophic collapse' (Winterwerp, 2001). By accounting for the stratification effects induced by cohesive sediments, Winterwerp (2001) reproduced collapse of the concentration profile. However, this phenomenon is not peculiar to flow with cohesive sediments. In their numerical studies in an oscillatory channel, Ozdemir et al. (2010) showed that under conditions of complex variation of the flow turbulence over a wave cycle, even a slight level of stratification can cause the formation of a lutocline. Further increase in stratification effects results in the suppression of turbulent production in the wave boundary layer which eventually leads to flow relaminarization and collapse of the concentration profile. The effect of stratification may significantly change the amount of water and sediment discharge. For example, McLean (1991) showed that in the presence of sediment suspension, the resistance coefficient may decrease by one order of magnitude, and the sediment discharge may decrease by two orders.

The model presented here accounts for the effect of density stratification through a two-way coupling between the flow and

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Nomenclature

Symbols

$\hat{b}$	reference height
C	depth-averaged volumetric concentration
$\hat{c}$	dimensionless total volumetric concentration
c'	fluctuation of concentration from total volumetric concentration
$\hat{c}_b$	dimensionless total near bed volumetric concentration
$\hat{c}_i$	dimensionless volumetric concentration of the *i*th size range
c_i'	fluctuation of concentration from volumetric concentration of the *i*th size range
D_g	geometric mean grain size [L]
D_i	grain size of the *i*th size range [L]
$E_{s,i}$	entrainment coefficient of the *i*th size range
g	gravitational acceleration [L/T^2]
h	water depth [L]
k	turbulent kinetic energy [L^2/T^2]
k_s	roughness height [L]
$\hat{k}$	dimensionless turbulent kinetic energy
$\hat{k}_s$	dimensionless roughness height
$\hat{l}$	dimensionless master length scale
N	number of size ranges
p_i^{bs}	volume fraction of the *i*th size range in the bed surface layer
p_i^{nb}	near bed volume fraction of the *i*th size range
p_i^{wc}	volume fraction of the *i*th size range in the water column
$\hat{q}^2$	dimensionless turbulent kinetic energy
R	submerged specific gravity
Re_{p*}	particle Reynolds number
Re_τ	shear Reynolds number
Ri_g	gradient Richardson number
Ri_τ	shear Richardson number
S	slope
Sc	Schmidt number
Sc_t	turbulent Schmidt number
$\hat{t}$	dimensionless time
$\hat{u}$	dimensionless velocity
$\widehat{u'w'}$	dimensionless Reynolds stress $\times(-1)$
u_*	shear velocity [L/T]
v_{si}	settling velocity of the *i*th size range [L/T]
$\hat{v}_{si}$	dimensionless settling velocity of the *i*th size range
$\widehat{w'c'}$	dimensionless total Reynolds flux
$\widehat{w'c_i'}$	dimensionless Reynolds flux of the *i*th size range
$\hat{z}$	dimensionless vertical coordinate
ε	energy dissipation [L^2/T^3]
$\hat{\varepsilon}$	dimensionless energy dissipation
κ	von Kármán constant
ν	kinematic viscosity [L^2/T]
ν_c	molecular diffusivity [L^2/T]
$\hat{\nu}_t$	eddy viscosity
$\hat{\nu}_{t0}$	eddy viscosity under neutral conditions
$\hat{\nu}_{tc}$	eddy diffusivity
ϕ_M	Monin–Obukov correction function

the suspended particles. The Reynolds-averaged Navier–Stokes (RANS) equations are solved with various turbulence closures to obtain the streamwise velocity and sediment concentration profiles in the vertical direction. A very similar model framework can be found in several previous studies to investigate sediment-induced stratification effects. Smith and McLean (1977) used a zero-equation model for the turbulence closure by applying the treatment for thermally stratified flows. Similar closures were used by Gelfenbaum and Smith (1986), Villaret and Trowbridge (1991), Herrmann and Madsen (2007), all using the model coefficients calibrated for open channel flows. Winterwerp (2001) and Hsu et al. (2009) used the k-ε model for turbulence closure to study the effect of density stratification in fluvial and coastal environments with the consideration for both cohesive and non-cohesive sediment. Wright and Parker (2004a) used a level 2 Mellor–Yamada model to investigate the effect of stratification on flow and sediment discharge. While these studies aimed at understanding the stratification effects for particular problems, no tool appears to have been developed to provide simple evaluation and visualization of such effects. In particular, for the case of equilibrium open channel flow, previous research provides no easy and direct way to evaluate how stratification causes the velocity and suspended sediment concentration to vary from the standard Vanoni–Rouse formulation given in standard texts on sediment transport. In the present work, we present the tool StratSedOC for such purpose.

In the following, we first present the problem setting and the equations and boundary conditions involved. The construction of the software is then presented. The model is tested with three experimental studies, which include runs under both below- and at-sediment-transport-capacity conditions. The results show that the boundary condition for the standard k-ε model is incapable of reflecting the effect of stratification at and near the bed. A modified boundary condition for the k-ε model is then proposed.

2. Theory

2.1. Problem setting

The problem setting for StratSedOC is shown in Fig. 1. A fully-developed steady, uniform open-channel flow of infinite width containing a sediment suspension is considered. The transport of the suspension is assumed to obey the following conditions:

(1) The concentration of the sediment suspension is sufficiently dilute so that the effect of hindered settling can be neglected.
(2) The particles in suspension are sufficiently small such that they follow closely the water movement up to a fall velocity. This condition also implies that the effect of suspended sediment is to damp the turbulence as well as the effective mixing rather than to increase them due to wake shedding from the particles. Nino and Garcia (1998) showed that this condition holds under the criterion $\mathrm{Re}_{p*}<2$, where $\mathrm{Re}_{p*}=u_*D_g/\nu$ is a particle Reynolds number, u_* is the shear velocity (to be defined later), D_g is the geometric mean grain size of the particles in suspension and ν is the kinematic viscosity. This suggests that for most natural streams, estuaries and coastal environments

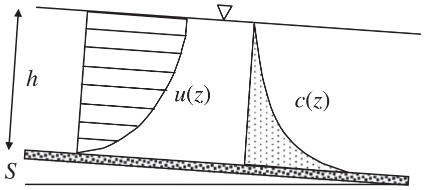

Fig. 1. Definition sketch for steady, streamwise-uniform open-channel flow with sediment suspension.