WALL-LAYER MODEL FOR LARGE EDDY SIMULATION (LES) OF SUSPENDED SEDIMENT TRANSPORT (SST) IN A LAB-SCALE TURBULENT OPEN CHANNEL FLOW

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ABSTRACT

In this study, a wall layer model under the equilibrium assumption and in the large eddy simulation (LES) framework is applied to simulate the suspension of the sand particles in a turbulent open channel flow of water. Smagorinsky model in the Euler-Euler model, which was developed in the LES-COAST code [1], is used to solve the subgrid-scale (SGS) stresses.

INTRODUCTION

We already know that the commonly observed flows in the rivers and fluvial channel are turbulent and unsteady. In such a flow, the 3D velocities change in time and space and there is an energy transfer between various scales present in the flow. Caused by the vortex stretching and tilting, the energy is transferred to smaller and smaller eddies and the mechanical energy is eventually converted into the heat.

The motion of the sand particles in the aforementioned flows is classified as the suspended sediment transport (SST) and bed-load transport (BLT) depending on the way sediments are carried in the flow. In the BLT, particles roll and slide over the bed when the fluid forces exceed the resisting force of the sediment such as weight and friction. As the turbulent forces become strong and the particles smaller and smaller, the SST happens. The suspension is a prevailing phenomenon if the particles are so small. The interaction between particles and the base fluid in the sediment laden flows is important from a geo-morphological viewpoint because it affects the sedimentation and erosion. Several theoretical, numerical and experimental studies at the laboratory-scale reported that the presence of the particles led to the alteration of turbulence and of velocity profile.

Pal et al. [2] theoretically found a velocity lag due to the particle-fluid interaction in the turbulent flow. Li et al. [3] analytically concluded that there was no difference between the mixed-flow model and two-phase flow model when the mean velocities of the mixture were estimated. Also, the RMS velocity of the mixture is not reliably indicative of the turbulence level in the sediment-laden flow. Rashidi et al. [4] experimentally analyzed the interactions between polystyrene and glass particles and fluid flow in wall turbulence. While smaller polystyrene particles caused a decrease in the intensity and the Reynolds stress, heavier glass particles did not alter those results. Muste et al. [5] recorded that the streamwise velocity of the sand sediment with the diameter of 0.21-0.25mm in the suspended transport mode was less than that of water. The mean velocity proved to be decreased with the sediment concentration throughout the depth and this effect became higher when the concentration increased more. Kiger and Pan [6] concluded that the presence of particles modified the carrier phase turbulence with an increase in the wall friction velocity and an increase of the normal and shear Reynolds stress. Noguchi and Nezu [7] experimentally found out that the turbulence in the sediment-laden flow may be enhanced or suppressed depending on the critical particle diameter.

Previous researchers proposed various numerical models to represent in detail the main features of the sediment laden flow. Based on how sediments are modelled in the turbulent flow, these models are the Euler-Lagrange (EL) or Euler-Euler (EE). In the Euler-Euler treatment, the governing equations for both fluid and sediment are obtained according to the continuum theory in the single-phase or two-phase framework. In the Euler-Euler single-phase model, fine particles are taken into account and suspended sediment transport is simulated through defining an advection-diffusion equation for the concentration. Also, in this model the suspended particles follow the fluid flow except for the vertical settling velocity. Also, the effect of the sediment concentration on the momentum equation called the two-way coupling which is characterized as the buoyancy force due to the density difference should be represented [8].

The turbulence closure models commonly in use are the 2D k-ε model using a two-phase approach [8], a 3D k-ε model in the single-phase viewpoint on the basis of the general-purpose FAST3D flow solver including the treatment of free surface and bed roughness [9], Reynolds stress model (RSM) and K-ω model based on the two-phase flow [10], a 3D two equation k-ε model for simulating the local sediment scour [11] and a 3D RNG k-ε turbulence model and a non-equilibrium wall function for studying the river bifurcation [12].

In recent years, large eddy simulation (LES) proved to be a technique to model a wide class of flows of interest also in environmental fluid mechanics. In LES, the large energy-carrying eddies which depend on the boundary conditions are directly resolved while the small eddies, which are more universal and isotropic, are modelled utilizing a sub-grid scale (SGS) model. Open channel flow as a wall-bounded flow especially at high Reynolds numbers demand a very fine mesh close to the walls in order to compute the viscous sub-layer. This requirement in the wall-resolving LES is like the direct numerical simulation (DNS). Hence, it would be computationally practical to solve the near-wall region using a wall-function instead of resolving it. The simplest approach in the unresolved wall-layer LES is the equilibrium stress model (ESM) in which the first computational node off the wall should be defined in the log region to express precisely the bottom shear stress to the outer region. This approach is the least expensive wall-layer model working well in conditions where there is no sharp separation or strong pressure gradient.

Change and Scotti [13] applied LES in the Euler-Lagrange two-way coupling framework to study the movement of the sediment particles on 2D sinusoidal ripples immersed in a turbulent flow.

Hai et al. [14] performed the LES-based rough wall model with a modified dynamic coherent eddy model instead of the LES with the near-wall resolution to investigate the non-cohesive suspended sediment transport in a turbulent channel flow with a high concentration. Regarding the streamwise direction, sediments were eroded mostly owing to the excess bottom shear stress, whereas in the spanwise one, the turbulent mixing created by the streamwise vortices contributed further to the erosion from the bed.

Net deposition of the fine sediment with the diameter of 0.1 mm in an open channel with various aspect ratios studied using the LES in the Euler-Euler single-phase framework by Bai et al. [15]. As the aspect ratio abated more, the deposition of the fine sediment hindered more and the turbulence enhanced.

Using LES together with the level-set method and pickup rate equation in the Euler-Euler single phase model, the turbulent channel flow and the suspended sediment on a migrating ripple-shaped bed were analyzed by Kraft et al. [16]. Harris and Grilli [17] developed a hybrid LES procedure in the one-way coupling in the EE single-phase modelling to study the wave-induced sediment transport over the sand ripples. Jourabian et al. [18] applied a wall-resolving LES with the dynamic Smagorinsky model (DSM) to examine the influence of the suspended sand particle on the turbulence statistics. Dallali and Armenio [19] used the Euler-Euler single-phase based LES to investigate the SST and its effect on the dynamics of the turbulent boundary layer.

In this study, the aim is to use the unresolved wall-layer LES in the Euler-Euler single-phase framework to understand the interaction between the suspended sand particles and turbulence in an open channel flow. The wall function is based on the ESM. The two-way coupling or the stratification effect is accounted for through defining a buoyancy term in the Navier Stokes (NS) equations.

NOMENCLATURE

B	[-]	Integration constant
C	[kg/m^3]	Concentration
C_s	[-]	Smagorinsky constant
d	[m]	Diameter of sand particles
f	[-]	Friction factor
g'	[m/s^2]	Modified gravity
k_s	[m]	Roughness
p	[N/m^2]	Pressure
Q	[m^3/s]	Mass flow rate in experiment
R_h	[m]	Hydraulic radius
Sc	[-]	Molecular Schmidt number
Sc_t	[-]	Turbulent Schmidt number
U	[m/s]	Bulk and mean streamwise velocity
V	[m/s]	Mean vertical velocity
W	[m/s]	Mean spanwise velocity
w_s	[m/s]	Settling velocity
x,x_1	[m]	Streamwise direction
y,x_2	[m]	Vertical direction
y_{ol}	[m]	The height of first grid point in the outer layer
z,x_3	[m]	Spanwise direction

Greek symbols

α	[-]	Volume fraction ratio
Δ	[m]	Filter width
δ	[-]	Kronecker delta
υ	[m^2/s]	Kinematic viscosity
θ	[-]	Shield variable
κ	[-]	Karman constant
τ	[N/m^2]	Shear stress
ω	[N/m^2]	SGS stress for concentration

FILTERED GOVERNING EQUATIONS

In the EE single-phase model, one advection-diffusion equation is defined to account for the space-time distribution of the volumetric concentration as the scalar quantity while the 3D NS equations are taken into account for the fluid flow in the channel.

The velocity of the sediment-laden flow (SLF) is equal to those of the fluid and sediment particles. But, the vertical velocity of the sediments in the EE single-phase model is equal to their settling velocity in a pure still water in a simplified treatment.

The flow in the SLF and clear water case (CWC) is incompressible. When analyzing the SST in a simple sense, the Boussinesq approximation for the buoyancy effects is introduced in the NS equations called the two-way coupling formulation. This approach is valid when the diameter of the particles and volumetric concentration are low hence the inter-particle interactions can be disregarded. Further, the sediments should be non-cohesive because the Newtonian law defined for the CWC fails.

In LES, the scale separation is accomplished by applying the low-pass filtering to the governing equations like [19],

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = \frac{1}{\rho_0}\Pi - \frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial x_i} - g'\delta_{i2} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \bar{\tau}_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial \bar{C}}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{u}_j - w_s \delta_{j2}\right)\bar{C} = \frac{\nu}{Sc}\frac{\partial^2 \bar{C}}{\partial x_j^2} - \frac{\partial \omega_j}{\partial x_j} \tag{3}$$

x or x_1 is the streamwise direction, y or x_2 is the vertical direction and z or x_3 is the spanwise direction. The over-bar means the filtered quantity. u_1, u_2 and u_3 are the instantaneous velocities of the mixture as a single phase in the streamwise, vertical and spanwise directions, respectively. Π is the imposed pressure gradient as the driving force in the numerical modelling.

The two-way coupling effect which means the sediment particles affecting the fluid flow is taken into account by introducing the stratification correction factor called the modified gravity term. This term and the relationship between the density and the volumetric concentration in the SLF are represented by the following,

$$g' = gC\frac{\rho_s - \rho_0}{\rho_0} \tag{4}$$

$$\rho = \rho_0 + (\rho_s - \rho_0)C \tag{5}$$

The subgrid-scale (SGS) stresses $\overline{\tau}_{ij}$ are here parametrized using the Smagorinsky model. In this SGS stress model, the small scales are in equilibrium and the SGS stresses are computed based on the eddy viscosity assumption. The SGS stresses are calculated as:

$$\overline{\tau}_{ij} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j = \left(C_s \overline{\Delta}\right)^2 \left|\overline{S}\right|, \quad \overline{\Delta} = 2(\Delta x \Delta y \Delta z)^{\frac{1}{3}} \tag{6}$$

$$\left|\overline{S}\right| = \left(2\overline{S}_{ij}\overline{S}_{ij}\right)^{0.5}, \quad \overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_i} + \frac{\partial \overline{u}_j}{\partial x_j}\right) \tag{7}$$

$$\omega_j = \overline{u_j C} - \overline{u}_j \overline{C} = -k_{sgs}\frac{\partial \overline{C}}{\partial x_j} \tag{8}$$

k_{sgs} is the SGS concentration diffusivity [20] obtained from the Smagorinsky model. $\left|\overline{S}\right|$ is the contraction of the resolved-scale strain-rate tensor. The turbulent Schmidt number (Sc_t), which characterizes the efficiency of the mixing in the SLF, is defined as the ratio of the turbulent eddy viscosity to the turbulent concentration diffusivity. More details can be found in [19].

UNRESOLVED WALL-LAYER LES

It is established that solving the near-wall region in the wall-bounded flows (WBF) particularly at high Reynolds numbers is heavy from a computational cost point of view. To avoid this, the effect of the wall-layer region should be modelled using a coarse grid close to the walls together with a wall model. Here, the wall model LES is based on the equilibrium stress model (ESM), and the first computational node off the bottom wall is located in the log region. This ESM is the amid the least-expensive wall-layer models working well when the turbulence is in the equilibrium and there is no flow separation. This model provides the roughness corrections by adapting the logarithmic wall. Moreover, the outer flow velocity is used to estimate the wall stress consistent with the logarithmic wall. The computational cost is mainly due to the calculation of the outer region flow. Therefore, the velocity in the first grid point in the outer layer is computed as,

$$U_{ol}^{+} = \frac{U_{ol}}{u_\tau} = \frac{1}{\kappa}\log\frac{y_{ol}u_\tau}{\nu} + B \tag{9}$$

This velocity is obtained after averaging over the xz-plane and time. As prescribed by Deardorff [21], the second-order derivatives of the streamwise and spanwise velocities in the vertical direction are demonstrated like,

$$\frac{\partial^2 \overline{U}}{\partial y^2} = -\frac{1}{\kappa y_1^2} + \frac{\partial^2 \overline{U}}{\partial z^2} \tag{10}$$

$$\frac{\partial^2 \overline{W}}{\partial y^2} = \frac{\partial^2 \overline{W}}{\partial x^2} \tag{11}$$

In this unresolved wall-layer LES [22] which is based on the equilibrium stress model (ESM), the shear velocity is analysed from the law of the wall like

$$\tau_{w,x}(x,z,t) = \frac{\overline{\tau}_w}{\overline{U}}\overline{U}(x, y_1, z, t) \tag{12}$$

$$\tau_{w,z}(x,z,t) = \frac{\overline{\tau}_w}{\overline{U}}\overline{W}(x, y_1, z, t) \tag{13}$$

SEDIMENT EROSION MECHANISM

The open-channel flows transport the total load of the sediment as the bed load occurring close to the bed and the suspended load happening along the total water height.

Choosing the appropriate sediment boundary condition at the bottom wall is one of the critical issues when defining the advection-diffusion equation for the sediment concentration as the scalar quantity. Basically, when the shear stress calculated on the bottom wall exceeds the critical one, the sediment would be entrained and suspended into the flow. Depending on the state of the flow, two boundary conditions may be prescribed called the reference concentration formulation [19, 23] and the pick-up rate function [24].

While in the unsteady sediment transport, previous researchers proposed the pick-up function for example in oscillatory flows, several experiments were performed to formulate the reference concentration at the reference level when the flow was in the equilibrium. The reference concentration is evaluated at 0.05×water height.

Here the expression for the reference concentration is taken like [19, 23],

$$\overline{C}_{ref} = C_0\frac{\gamma_0 \overline{S}_0}{1+\gamma_0 \overline{S}_0}, \quad \overline{S}_0 = \frac{\overline{\tau}_w - \tau_{cr}}{\tau_{cr}} \tag{14}$$

$$\gamma_0 = 2.4\times 10^{-3}, \; C_0 = 0.65$$

As could be seen, this reference concentration is quantified as a function of the instantaneous bed shear stress and critical bed shear stress. It manifests the capability of the flow to suspend the sediment on the bed. In this study the critical shear stress is estimated from the Shields diagram which establishes a relationship between the critical Shields variable and the dimensionless particle size by [19],

$$\theta_{cr} = \frac{\tau_{cr}}{(\rho_s - \rho_0)gd} \tag{15}$$

$$d^+ = \frac{u_\tau d}{\nu} \tag{16}$$

For treating the suspended sediment transport (SST), a third variable representing the inclined parallel lines is introduced [19],

$$S_S = \frac{d}{\nu}\left[0.1\left(\left(\frac{\rho_S}{\rho_0} - 1\right)gd\right)\right]^{0.5} \tag{17}$$

The instantaneous bed shear stress is determined from [19],

$$\overline{\tau}_w = \sqrt{\overline{\tau}_x^2 + \overline{\tau}_z^2} \tag{18}$$

In the right-hand side (RHS), the bed shear stresses in the streamwise and spanwise directions are included.

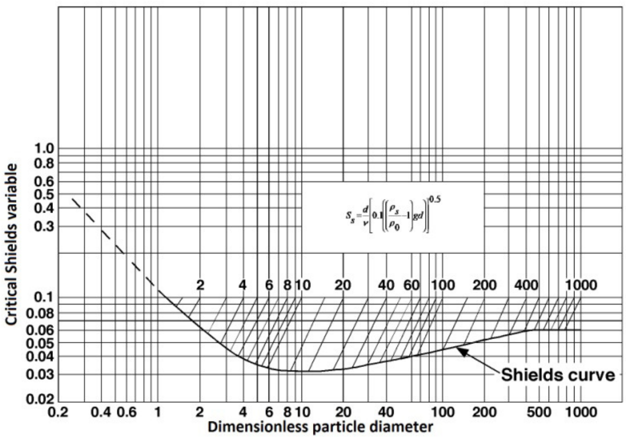

Figure 1 Shields diagram

EXPERIMENTAL DATA

Graf and Cellino [25] performed experiments on the sediment-laden flow in a recirculating tilting open channel.

Table 1 variables defined in experiment of Cellino

	CWC (CW_S015)	SLF (Q40S003)
Q (m^3/s)	0.05	0.049
h (m)	0.12	0.12
AR	5.0	5.0
U (m/s)	0.726	0.68
S_b (%)	0.15	0.03
Re	248900	233000
Fr	0.67	0.63
u_τ (m/s)	0.045	0.028
F	0.031	0.014
k_s (m)	0.0012	0.00005
d_{50} (m)	-	0.000135
ρ_s (kg/m^3)	-	2650
w_s (m/s)	-	0.00012
C_s^m (kg/m^3)	-	2.05
ρ_m (kg/m^3)	1000	1001.28

Dimensions are of 16.8m, 0.12m and 0.6m, in the streamwise, vertical and spanwise directions, respectively. The pertinent variables in the experimental setup regarding the CWC and SLF are shown in Table 1. The SLF is steady and uniform carrying sand sediment at the capacity condition meaning the suspension flow over a fixed bed.

As stated by Graf and Cellino [25], this aspect ratio 5 means the flow is two dimensional (2D). The von Karman constant for both the CWC and SLF is equal to 0.4. Friction factor (*f*) is defined as [25],

$$f = 8\left(\frac{u_\tau}{U}\right)^2 \tag{19}$$

The nominal particle diameter (d_{50}), density (ρ_s) and settling velocity (w_s) in the clear still water are equal to 0.135mm, 2650kg/m^3 and 12mm/s, respectively. The kinematic viscosity of the mixture SLF is taken from Einstein [25],

$$\nu_m\left[\frac{m^2}{s}\right] = \nu.\frac{\rho_0.(1+2.5C_s)}{\rho_0 + (\rho_s - \rho_0)C_s} = 1.002 \tag{20}$$

To understand whether the flow is hydraulically smooth or transitional, the particle Reynolds number and roughness (k_s) should be calculated [25]:

$$\mathrm{Re}_p = \frac{u_\tau k_s}{\nu_m} = 1.4 \tag{21}$$

$$\sqrt{\frac{1}{f}} = -2.\log\left(\frac{k_s/R_h}{a_f} + \frac{b_f}{\mathrm{Re}\sqrt{f}}\right) \tag{22}$$

$$a_f = 11.5\ ,\ b_f = 3$$

Here it is found that the fluid flow is hydraulically smooth. The depth-averaged mixture density is equal to,

$$\overline{\rho}_m = \rho_0 + (\rho_s - \rho_0)C_s \tag{23}$$

Toorman [26] described that due to the lack of the experimental data on the fluid movement, the turbulent fluctuations of the fluid and sediment particles are supposed to be the same. The mean vertical particle velocity in the experiment called Q40 is nonzero approximately in the order of the Stokes settling velocity because of the existence of the high-concentration effects in the layer close to the bottom, wake effect near the surface and secondary currents.

SIMULATION RESULTS

In the LES-COAST code [1], the unresolved wall-layer LES is chosen to analyze the interaction of the suspended sediment with the turbulence in the experiment of Graf and Cellino [25].

In the numerical simulation, the channel dimensions in the x, y and z directions are equal to 2×π×0.12m, 0.12m and π×0.12m, respectively. The total number of the cells is 32×32×32. Both the molecular and turbulent Schmidt numbers are set to 1.0. In both SLF and CWC, the constant in the Smagorinsky model is C_s=0.065. The Courant number in this study is equal to 0.2 meaning that the time step (Δt) changes over time around 2×10^{-3} to get the fixed Courant number,

$$\overline{\rho}_m = \rho_0 + (\rho_s - \rho_0)C_s \tag{24}$$

The flow is driven by imposing a constant pressure gradient divided by the water density and it is equal to 0.021 and 0.0081 in the CWC and SLF, respectively. To compute the imposed pressure gradient, wall shear stress on the sidewalls has to be specified. According to [27], the value of shear stress on each sidewall is equal to 0.63×bottom shear stress.

The same roughness as expressed in the experiment is applied separately for the CWC and SLF. In addition, the no-flux condition for the concentration is defined for the top free surface while the periodic boundary condition is set in the streamwise and spanwise directions.

The initial state of the open channel flow was obtained by interpolating from a highly turbulent closed channel flow. After reaching the steady state, the statistics of the CWC obtained and then an initial constant profile of the sediment volumetric concentration 0.000773 is set to get the SLF through activating the buoyancy and roughness effects.

Figure 2 demonstrates the effect of the suspended sediment on the depth-averaged streamwise velocity. It should be stated that the bulk velocity in the CWC and SLF is equal to 0.73 (m/s) and 0.69, respectively. Hence the maximum error is around 2 percent. Also, the friction velocity in the CWC and SLF is 0.049 (m/s) and 0.03 (m/s), respectively. It has to be commented that the first y^+ off the bottom wall in the SLF case is equal to 56.25. In accordance with the result of Muste et al. [5], it is understood that the streamwise velocity is reduced in the upper saturated region while the flow is accelerated in the super-saturated region close to the bottom wall because of the high inter-particle collisions between particles.

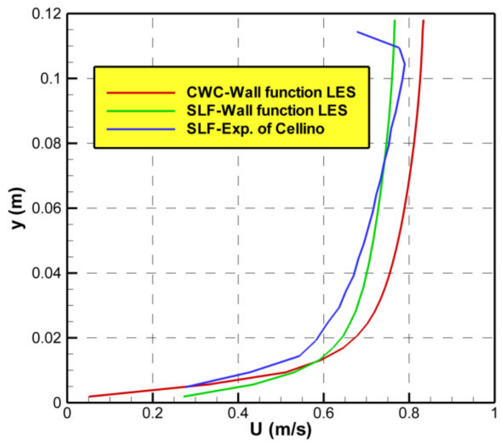

Figure 2 Depth-averaged streamwise velocity

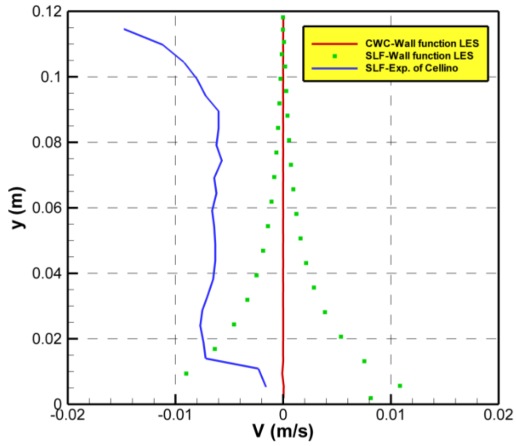

Figure 3 Depth-averaged vertical velocity

Figure 3 demonstrates the effect of the suspended sediment on the depth-averaged vertical velocity. A positive value means that the velocity is directed upward to the free surface. The vertical velocities are too small in comparison with the streamwise velocities.

The Reynolds stresses obtained in the experiments and numerical modelling regarding CWC and SLF are shown in Figure 4. The parenthesis (-) in this figure means averaging over the horizontal planes and time. Pay attention that in the viscous sub-layer region the Reynolds shear stress is negligible compared to the viscous stress and the linear variation of the Reynolds shear stress after some distance from the wall is taken as the evidence of the fully developed channel and equilibrium state of the flow.

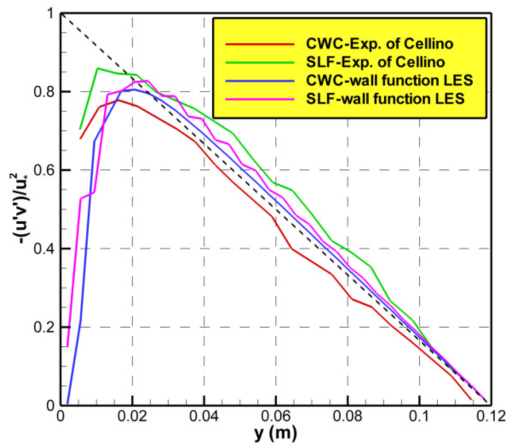

Figure 4 Depth-averaged Reynolds stress

As also shown by Graf and Cellino [25] in Figure 5, the streamwise turbulence intensity (TS_u) in the SLF is comparable to that in the CWC. Adjacent to the bottom wall, it is enhanced.

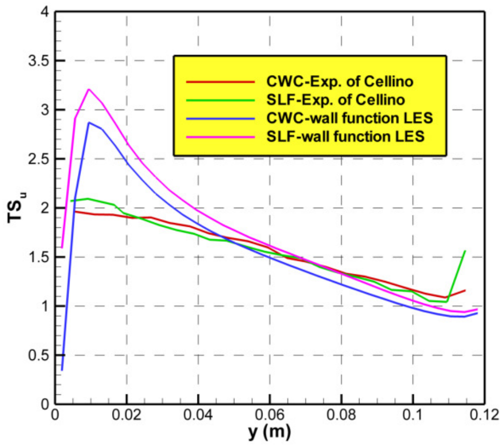

Figure 5 Depth-averaged streamwise turbulence intensity

In Figure 6, it is shown that the presence of the suspended sediments attenuated uniformly the vertical turbulence intensity along the total depth of the water.

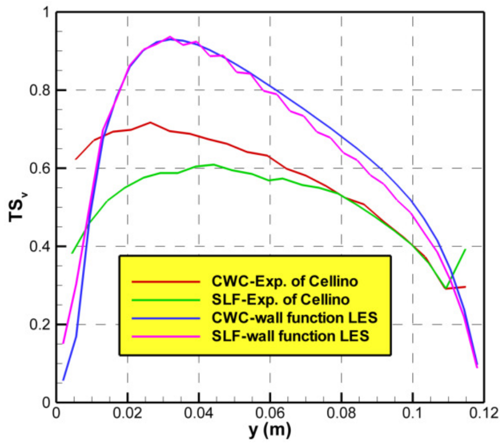

Figure 6 Depth-averaged vertical turbulence intensity

In Figure 7, we compare the volumetric concentration against the experimental data. When the buoyancy term is switched-off, the value of the volumetric concentration is high and unsatisfactory results gathered.

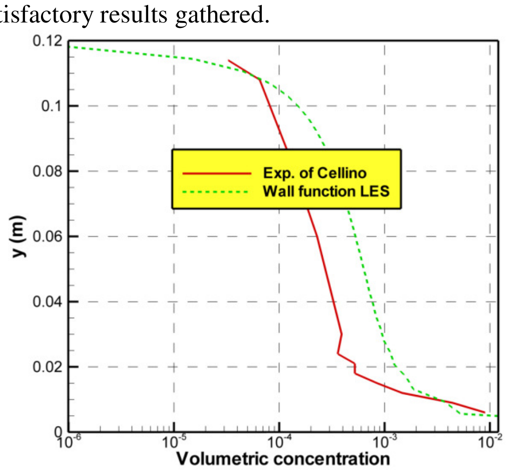

Figure 7 Depth-averaged volumetric concentration

Activating the buoyancy led to the accumulation of the sediment toward the bottom. Similar to the study of Toorman [26], the experimental results are underestimated close to the free surface. In the experiment, the streamwise velocity deviated from the logarithmic profile due to the existence of the secondary currents and near the free surface large velocity gradients produced more turbulence and suspension of the sand particles compared to the numerical results which based on the wide channel assumption.

CONCLUSIONS

An unresolved wall function LES based on the Smagorinsky model is developed under the Euler-Euler single-phase framework [28] to comprehend the interactions of the suspended sand sediment with the turbulence in a highly turbulent open channel flow. The wall function is based on the ESM. The flow remains Newtonian after adding the sand sediment into water and the two-way coupling effect is included through introducing a modified gravity term in the NS equations. The sediment erosion mechanism on the bottom wall is defined based on the reference concentration while the no-flux condition for the concentration selected at the free surface. It is understood that the stratification effect originating from the change of density in the total water depth should be taken into account to get a better accuracy of the numerical results.

When suspending the sand sediment in the turbulent open channel flow, the streamwise velocity decreases in the upper saturated region while the flow accelerates in the super-saturated region near the bottom wall because of the high collisions between particles. In terms of the bulk velocity and shear velocity, the simulation error is less than 2 percent when validating the CWC and SLF against the existing experimental data. It is recorded that the presence of the suspended sediment weakened uniformly the vertical turbulence intensity along the total depth of the water while the effect on the depth-averaged streamwise turbulence intensity was insignificant totally. Close to the free surface, the sediment volumetric concentration obtained from the LES was lower than that of the experimental test because the streamwise velocity deviated from the logarithmic profile in the experiments due to the existence of the secondary currents. Plus, in the experiment near the free surface the large velocity gradients produced more turbulence and suspension. As discussed by [26], it must be mentioned that generally the low sediment concentration reported close to the free surface in experiment is not very accurate because they are so low and difficult to be captured by the measuring instrument. On the contrary, this work and previous studies [26] are based on the theory of the infinite wide channels so secondary flows close to the free surface could not be regarded.

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