Analysis of turbulence suppression in sediment-laden saline currents

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Abstract

The present work extends the results of Cantero et al.[1] and Shringarpure et al.[2] to the cases of sediment-laden saline currents. The flow is modeled as a channel flow where the forcing is exerted by salinity and suspended sediments. The resulting set of equations are solved by direct numerical simulation (DNS) for shear Reynolds number $Re_τ = 180$. The DNS results show that by increasing the forcing due salinity, the flow can be held in a turbulent state whereby large sediment particles can be maintained in suspension. Typically, such large sediment particles would not be able to sustain the flow by themselves. The DNS results also show that for large sediment loads there is a transition to total turbulence suppression. This transition is abrupt and is caused by small changes in the sediment load. Here, salinity can be interpreted as a fraction of sediments that are fine enough that their settling velocity is negligible. Thus, the case of sediment-laden saline currents is physically equivalent to a simplified bi-disperse model where the fine sediments do not settle. Finally, this work shows that the original results by Cantero et al.[1] and Shringarpure et al.[2] hold when they are reinterpreted under the light on an effective settling velocity.

Keywords: Gravity currents; Sediments; Turbidity currents; Turbulence suppression; Geophysical flows; Multiphase flows;

1. Introduction

Gravity currents are buoyancy driven flows where the direction of flow is predominantly orthogonal to the direction of gravity. There are several examples of such flows in geophysical, environmental and industrial processes - snow avalanches, dust storms, pyroclastic flows, lava flows, leakage of poisonous fluid in the environment and dam breaks are just some examples [3]. Typically, such flows are extremely energetic and highly turbulent. In the ocean environment they are responsible for transporting sediments over large distances [4,5,6].

In this work the primary focus is on sediment-laden saline currents. These flows can be conceptualized as submarine rivers that transport variety of dispersed matter in suspension to deep ocean [7]. Through their downstream propagation, these currents can exhibit phases of strong erosion and deposition. Recurring occurrences of such currents are known to carve out different topographies on the ocean floor. Some of the huge submarine canyons are

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testimony of the erosive nature of such currents [5]. When these currents are primarily driven by suspended sediments they are known as turbidity currents.

Sediment-laden saline currents can have complex dynamics based on various factors like the amount of suspended sediments, ocean bed topography, ambient entrainment at the top and sediment properties. Here, we restrict our attention to dilute flows (volumetric concentration of suspended sediments is usually less that 1%) so that turbulence in the flow is the sole mechanism responsible for entraining sediments from the bed and keeping them in suspension. Even under such conditions, the suspended sediment particles are locked into a tight interplay with turbulence. The settling tendency of sediments could lead to density stratification which would strongly interact with the flow turbulence diminishing the ability of the current to erode sediments from the bed and to maintain the suspended load.

The interplay of turbulence and suspended sediment has been studied in Cantero et al.[8] by means of direct numerical simulations (DNS). They modeled these currents as inclined channel flows driven by the excess density imposed by a mono-dispersed suspension of sediment. Cantero et al.[8] and Cantero et al.[9] reported complete turbulence suppression when the settling velocity of sediments was greater than a critical value. Complete turbulence suppression implies that the flow has lost the capacity to keep the sediments in suspension [10]. In Shringarpure et al.[2] the complete turbulence suppression process was analyzed in greater detail and a mechanism that causes complete turbulence suppression in the flow was proposed.

This mechanism of complete turbulence suppression is parameterized in Cantero et al.[1]. It is suggested that turbulence suppression can be quantified by the parametric grouping \( R_i V_z / u^* \), which also represents the amount of energy spent by turbulence to keep the settling sediments in suspension. Here \( R_i \) is the shear Richardson number which simplifies to \( 1 / \tan \theta \) for a turbidity current where \( \theta \) is the angle of the bed with respect to the horizontal direction, \( V_z \) is the settling velocity of the suspended sediments in the direction normal to the bed, and \( u^* \) is the shear velocity of the flow. Cantero et al.[1] propose that complete turbulence suppression will occur in a flow corresponding to a supercritical value of \( R_i V_z / u^* \). Furthermore, it is noted that the critical value will depend on the shear Reynolds number of the flow \( (Re_c) \). Limited field and experimental observations, and DNS results suggest a logarithmic dependence on \( Re_c \).

The present work extends the critical turbulence suppression criteria [1] to saline currents with additional suspended sediments. The flow and turbulence are thus driven by both salinity and suspended sediments, while stratification is only due to suspended sediments. We will investigate turbulence suppression in this context. Clearly, in the limit of no suspended sediment turbulence will not be suppressed. Furthermore, since turbulence is partially driven by salinity, the current could carry sediments of large size and at larger volume fractions than what it could have in the absence of salinity. The criterion for turbulence suppression can no longer depend only on the suspended sediments, but also include the effect of added salinity that drive the current. This new aspect is the focus of the present paper.

2. Problem formulation

This section describes the mathematical model for dilute sediment-laden saline currents driven in part by salinity and a mono-disperse suspension of sediment. This mathematical model extends the mono-disperse model presented in Cantero et al.[8] and [2]. See Figure 1 for a schematic representation of the mathematical model. Here we assume that the mono-disperse suspension is dilute enough, sediment particle-particle collisions are unimportant and rheology effects can be neglected. The Equilibrium-Eulerian model is used to describe the dynamics of the flow (see Ferry and Balachandar[11] and Cantero et al.[12] for details on the Equilibrium-Eulerian model). Moreover, as a consequence of dilute suspension, Boussinesq approximation is also employed. Following are the dimensionless governing equations for such a flow

\[
\begin{align*}
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} &= -\nabla \tilde{p} + \frac{1}{Re_T} \nabla^2 \mathbf{u} + (\gamma \tilde{c} + \gamma_s) \mathbf{e}, \\
\nabla \cdot \mathbf{u} &= 0, \\
\frac{\partial \tilde{c}}{\partial t} + (\mathbf{u} + \mathbf{V}) \cdot \nabla \tilde{c} &= \frac{1}{Pe_T} \nabla^2 \tilde{c}.
\end{align*}
\]
In the above, \( \tilde{\cdot} \) represents dimensionless variables, \( \tilde{\mathbf{u}} = (\tilde{u}, \tilde{v}, \tilde{w}) \) is the fluid velocity, \( \tilde{p} \) is the pressure, \( \tilde{c} \) is the volumetric concentration of sediment, \( \mathbf{e} = (1, 0, -Ri_\tau) \) and \( \mathbf{V} = \{\tilde{V}_x, 0, -\tilde{V}_z\} \) is the settling velocity of the sediment particles. The form of the convection term in the concentration transport equation (3) implies that the sediment particles have small response time and their inertia is of second order importance as compared to their settling [8,11,12].

The dimensionless numbers in (1)-(3): the shear Reynolds number \( Re_\tau = \frac{u_* h}{\nu} \), the shear Richardson number \( Ri_\tau = \frac{g z h (RC^{(v)} + \Delta \rho_s/\rho_w)}{u_*^2} \), the shear Péclet number \( Pe_\tau = \frac{u_* h}{\kappa} \), and the remaining dimensionless parameters are defined as

\[
Re_\tau = \frac{u_* h}{\nu}, \quad Ri_\tau = \frac{g z h (RC^{(v)} + \Delta \rho_s/\rho_w)}{u_*^2} = \frac{1}{\tan \theta}, \quad Pe_\tau = \frac{u_* h}{\kappa},
\]

\[
\gamma = \frac{RC^{(v)}}{\Delta \rho_s/\rho_w + RC^{(v)}} \quad \text{and} \quad \gamma_s = \frac{\Delta \rho_s/\rho_w}{\Delta \rho_s/\rho_w + RC^{(v)}},
\]

(4)

Here, \( \nu \) is the kinematic viscosity, \( \rho_w \) is the density of fresh water, \( \Delta \rho_s \) is the density excess by salinity, \( \kappa \) is the diffusivity of sediments,

\[
C^{(v)} = \frac{1}{h} \int_0^h \tilde{c} \, dz,
\]

and

\[
R = \frac{\rho_p - (\rho_w + \Delta \rho_s)}{\rho_w}.
\]

(5)

where \( \tilde{c} \) is horizontal averaged normalized concentration. It should be noted that sediment diffusivity is not due to brownian motion of sediment particles, but due to the long range hydrodynamic forces mediated through the continuous phase due to random fluctuations in the particle number density [13,14]. This diffusive term also acts as a mechanism to erode or entrain sediments from the bed [15].

In defining the dimensionless variables, the friction velocity

\[
u_*^2 = \frac{\tau_b}{\rho_w} = g z h \left( RC^{(v)} + \Delta \rho_s/\rho_w \right),
\]

(6)

the height of the channel \( L_z = h \) and the volume concentration of sediment \( C^{(v)} \) have been used. Time and pressure scales are derived scales as \( h/u_* \) and \( \rho_w \nu_*^2 \), respectively.

The channel streamwise and spanwise lengths are \( L_x = 4\pi h \) and \( L_y = 4\pi h/3 \), respectively. The channel is assumed to be periodic in the streamwise and spanwise directions. No-slip boundary condition is imposed on the bottom boundary, and the top boundary imposes no-stress condition. For the sediment, bottom and top boundary of the channel imposes zero net flux of sediment concentration by enforcing the local settling flux of sediments to balance the local sediment concentration gradient. All the above boundary conditions can be mathematically expressed as follows

\[
\tilde{\mathbf{u}} = 0 \quad \text{at} \quad \tilde{z} = 0, \quad (7)
\]

\[
\frac{\partial \tilde{u}}{\partial \tilde{z}} = 0, \quad \frac{\partial \tilde{v}}{\partial \tilde{z}} = 0 \quad \text{and} \quad \tilde{w} = 0 \quad \text{at} \quad \tilde{z} = 1, \quad (8)
\]

\[
-\tilde{c} \tilde{V}_z = \frac{1}{Pe_\tau} \frac{\partial \tilde{c}}{\partial \tilde{z}} \quad \text{at} \quad \tilde{z} = 0 \quad \text{and} \quad \tilde{z} = 1. \quad (9)
\]
The flow modeled in this work is driven by the excess density imposed by salinity ($\gamma_s$) and suspended sediment ($\gamma_f$). Notice, however, that salinity will have no stratification and thus will not induce turbulence damping. On the other hand, due to their settling tendency, sediment particles will skew the driving force close to the bed and will stratify the flow in the bed-normal direction. Therefore, for the flows modeled in this work, the sediment is solely responsible for inducing turbulence damping effects. This effect is embodied by the term $Ri_\gamma$ in the wall-normal momentum equation. This work addresses systematically the influence of $\gamma$ on turbulence. While the total forcing of the flow is maintained ($\gamma + \gamma_s = 1$), by changing the fraction of forcing that modifies turbulence through stratification ($\gamma$) we explore turbulence suppression.

2.1. Selection of parameters

In this work, the inclination of channel is fixed at $\theta = 5^\circ$, that is $Ri_\gamma = 11.43$. This value is selected as it lies well within the range of inclination observed for the continental slope on the ocean floor (its range is $1^\circ$ to $10^\circ$, see Pinet[16]). Also $\theta = 5^\circ$ was the inclination used in the previous DNS simulations [1, 2, 8]. Shear Reynolds and Péclet numbers have been set to $Re_\gamma = Pe_\gamma = 180$ [2, 8].

Previous direct numerical simulations of the body of a turbidity current [2, 8] at same values of $Re_\gamma$ and $Ri_\gamma$ have shown that if $|\tilde{V}| < |\tilde{V}_{critical}|$ stratification effect is not strong enough to greatly alter the level of turbulence. These flows are driven only by suspended sediments and a critical sediment settling velocity, $|\tilde{V}_{critical}|$, is observed which when crossed resulted in total suppression of turbulence. In the presence of added salinity driving the flow, we can anticipate the critical settling velocity for turbulence suppression to be larger. Thus, in the present problem of sediment-laden saline currents the mechanism of turbulence suppression by changes in the sediment load is only of interest when $|\tilde{V}| > |\tilde{V}_{critical}|$. In this case there exist a critical value of $\gamma_s$ below which stratification effects due to sediments become strong enough to cause complete turbulence suppression. Note that for the case of $\gamma_s = 1$ there would be no stratification effects. We have performed DNS of the flow for three sets under different conditions. For every set $\tilde{V}$ is held fixed and $\gamma_s$ is varied to obtain its critical value below which there is complete turbulence suppression in the flow. We have employed $|\tilde{V}| = 0.0275, 0.035$ and 0.05 in set A, B and C, respectively. The details of all the simulations are given in Table 1.

3. Numerical method

The dimensionless governing equations (1)-(3) are solved using a dealiased pseudo-spectral code [17]. The flow variables are approximated by Fourier expansions in the direction tangential to the bed ($\tilde{x} - \tilde{y}$) and by Chebychev expansions in the bed-normal direction ($\tilde{z}$). Momentum equation along with the incompressibility criteria is solved by a splitting method. A low-storage mixed third order Runge-Kutta and Crank-Nicolson scheme is used for temporal discretization of advection and diffusion terms. This scheme is carried out in three stages with pressure correction at the end of each stage. Refer to Cortese and Balachandar[18] for complete details on the implementation of the scheme. The grid resolution of $(N_x, N_y, N_z) = (96, 96, 97)$ is used and it is found to be sufficient for the Reynolds number selected in this study [2, 8]. Averaged values are indicated by an overbar and computed by time integration over 50 dimensionless time units [2].

4. Results

In sediment-laden saline currents the extent of stratification depends on the relative magnitude of the settling tendency of sediments and turbulent mixing in the flow. Since the suspended sediments are also responsible for driving the flow, there is tight interplay between stratification and turbulence modulation by sediment. The volumetric concentration of sediment will impose a body force on the current. The streamwise component will contribute towards generating turbulence, while the bed-normal component will contribute towards stratifying the flow. Thus, if the net stratification is weak the current remains active and turbulence is sustained, otherwise, strong stratification can lead to complete turbulence suppression and the flow will cease to carry suspended sediment.

DNS are performed for three sets (A, B and C) where the settling velocity of sediments is fixed (0.0275, 0.035 and 0.05) and the proportion of salinity to sediment forcing is varied. In each set we start with a suspension mainly driven
by salinity ($\gamma_s \approx 1$) which keeps the stratification effects to zero. In subsequent cases, the forcing due to sediments is increased at the expense of salinity forcing. Thus we increase the stratification effect in the flow while keeping the total forcing constant. Eventually, a critical composition is reached so that even a small increase in the amount of sediments will result in complete turbulence suppression. The critical suspension lies between cases 6A and 7A for set A, 6B and 7B for set B and 6C and 7C for set C. Complete details of all the simulations are listed in Table 1. The value $\gamma_s = 1$ implies that the current is driven by a uniform forcing due to salinity. The case $\gamma_s = 1$ is used as a reference to compare the stratification effects of different suspensions.

Figure 2 (a) presents the sediment concentration profiles in the bed-normal direction for cases 1B, 3B, 6B, 7B. From case 1B to 7B, the amount of sediments in the suspension is progressively increased. The concentration at the bed increases from 1.232 for case 1B to 5.036 for case 7B. Similarly, the concentration gradient near the bed increases from case 1B to case 7B. Observe that from case 6B to case 7B there is a sudden change in the concentration profile. In case 7B most of the sediments are now concentrated close to the bed indicating loss in the mixing ability of the flow. Also shown in the figure are square symbols that represent the laminar solution [2] corresponding to the parameters of case 7B. The results indicate that complete turbulence suppression has occurred in case 7B.

Mean velocity profiles shown in Figure 2(b) also tell a similar story. From case 1B to 7B as the stratification increases it inhibits the vertical exchange of momentum and, as a consequence, the mean streamwise velocity. Similar to the concentration profiles, a substantial change in the $\bar{u}$ profiles is seen from case 6B to 7B. There is an abrupt jump in the bulk velocity and the maximum streamwise velocity from case 6B to case 7B.

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Figure 3(a) presents the Reynolds stress ($\tilde{u}'\tilde{w}'$) profiles of different cases from set B. Reynolds stress modulations are an indication of turbulence suppression and hence it represents the stratification effect on the flow. Reynolds stress profiles show slight damping as $\gamma_s$ decreases from 0.75 for case 1B to 0.24 for case 6B. Beyond case 6B, even a slight

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Table 1. List of simulations: $\gamma_s$ refers to the forcing fraction by salinity and $\gamma = 1 - \gamma_s$ is the forcing fraction by sediments. $\tilde{u}_b$ is the bulk streamwise velocity, $\bar{u}_t$ is the maximum mean streamwise velocity, $\tilde{c}_b$ and $\tilde{c}_t$ are the concentration of sediments at the bed and at the top boundary of the channel, respectively. The abbreviation CTS stands for complete turbulence suppression.

| case | $|\tilde{V}|$ | $\gamma_s$ | $\gamma$ | $\tilde{u}_b$ | $\bar{u}_t$ | $\tilde{c}_b$ | $\tilde{c}_t$ | State  |
|------|-----------|-----------|----------|-------------|-------------|-------------|-------------|--------|
| 1A   | 0.0275    | 0.75      | 0.25     | 15.91       | 18.96       | 1.167       | 0.90        | Turbulent |
| 2A   | 0.0275    | 0.50      | 0.50     | 16.59       | 20.07       | 1.371       | 0.776       | Turbulent |
| 3A   | 0.0275    | 0.30      | 0.70     | 17.19       | 21.07       | 1.572       | 0.644       | Turbulent |
| 4A   | 0.0275    | 0.125     | 0.875    | 17.88       | 22.15       | 1.799       | 0.499       | Turbulent |
| 5A   | 0.0275    | 0.06      | 0.94     | 18.23       | 22.65       | 1.911       | 0.437       | Turbulent |
| 6A   | 0.0275    | 0.04      | 0.96     | 18.41       | 22.91       | 1.951       | 0.415       | Turbulent |
| 1B   | 0.035     | 0.75      | 0.25     | 16.06       | 19.22       | 1.232       | 0.881       | Turbulent |
| 2B   | 0.035     | 0.50      | 0.50     | 16.88       | 20.60       | 1.540       | 0.717       | Turbulent |
| 3B   | 0.035     | 0.45      | 0.55     | 17.19       | 21.08       | 1.609       | 0.676       | Turbulent |
| 4B   | 0.035     | 0.30      | 0.70     | 17.78       | 22.28       | 1.880       | 0.546       | Turbulent |
| 5B   | 0.035     | 0.26      | 0.74     | 18.35       | 22.76       | 1.988       | 0.507       | Turbulent |
| 6B   | 0.035     | 0.24      | 0.76     | 18.44       | 22.90       | 2.027       | 0.4877      | Turbulent |
| 7B   | 0.035     | 0.235     | 0.765    | 30.63       | 39.96       | 5.036       | 0.244       | CTS     |
| 1C   | 0.05      | 0.75      | 0.25     | 16.48       | 19.84       | 1.402       | 0.8422      | Turbulent |
| 2C   | 0.05      | 0.60      | 0.40     | 17.32       | 21.18       | 1.741       | 0.720       | Turbulent |
| 3C   | 0.05      | 0.55      | 0.45     | 17.75       | 21.77       | 1.895       | 0.673       | Turbulent |
| 4C   | 0.05      | 0.50      | 0.50     | 18.15       | 22.40       | 2.065       | 0.622       | Turbulent |
| 5C   | 0.05      | 0.475     | 0.525    | 18.44       | 22.81       | 2.168       | 0.597       | Turbulent |
| 6C   | 0.05      | 0.469     | 0.531    | 18.51       | 22.90       | 2.198       | 0.593       | Turbulent |
| 7C   | 0.05      | 0.46      | 0.54     | 35.38       | 49.33       | 5.302       | 0.466       | CTS     |
drop in $\gamma_s$ to 0.235 (case 7B) causes abrupt and complete suppression of Reynolds stress in the flow. Figure 3(b) shows the profiles of ratio of Reynolds flux ($\tilde{w}'\tilde{c}'$) to settling flux $\bar{V}\tilde{c}$ for different cases from set B. Since Reynolds flux is a measure of turbulent mixing in the bed-normal direction, the ratio of Reynolds flux to settling flux represents the bed-normal mixing ability of the flow. Similar to Reynolds stress profiles, we observe that from case 1B to case 6B only slight damping is seen in the mixing ability of the flow. But, beyond case 6B there complete loss of the mixing ability of the flow. In summary, all of the above turbulence statistics reveal that complete turbulence suppression occurs when $\gamma_s$ is reduced from 0.24 to 0.235. This implies that at $Re_t = 180$ and slope $\theta = 5^\circ$, to transport sediments with $\bar{V} = 0.035$, salinity needs to make up at least 24% of the total flow forcing. Similar observations can be made from the other two sets, A and C. This is the underlying principle that gives gravity currents that are driven by salinity, or equivalently very fine sediments, the ability to transport large sediment sizes, which could not be carried in suspension otherwise.

4.1. Complete turbulence suppression criteria for sediment-laden saline currents

Cantero et al.[1] propose that turbulence damping can be quantified by the parametric grouping $Ri_t\bar{V}_c$ for a turbidity current driven by a mono-disperse suspension. In addition, it was also shown that the abrupt and complete turbulence suppression occurs when the parametric grouping $Ri_t\bar{V}_c$ increases beyond a critical value. Cantero et al.[1] also
proposes that the critical value for $R_{t, V_c}$ has a logarithmic dependence on $Re_r$. A similar analysis can be done for the case of a sediment-laden saline current and a similar parametric grouping can be given to quantify turbulence damping. Furthermore, it is also shown that a critical value for this parametric grouping exist that is similar to the previous mono-disperse case.

Turbulent kinetic energy (TKE) equation for a sediment-laden saline current when the flow is in statistically steady state is given below

$$\tilde{\Phi} - \tilde{\epsilon} - \frac{d}{d\tilde{z}} \left[ \tilde{w}'\tilde{P}' + \tilde{k}' - \frac{1}{Re_r} \frac{d\tilde{k}}{d\tilde{z}} \right] = -\gamma \tilde{u}'\tilde{v}' + \gamma R_{t, \tilde{V}_c} \tilde{w}'\tilde{v}'$$

(10)

where TKE $\tilde{k}$, TKE production $\tilde{\Phi}$ and TKE dissipation $\tilde{\epsilon}$ are expressed as

$$\tilde{k} = \frac{\tilde{u}'\tilde{u}'}{2}, \quad \tilde{\Phi} = -\tilde{w}'\tilde{w}' \frac{d\tilde{u}}{d\tilde{z}} \quad \text{and} \quad \tilde{\epsilon} = \frac{1}{Re_r} \frac{\partial \tilde{u}_i'}{\partial \tilde{x}_j} \frac{\partial \tilde{u}_j'}{\partial \tilde{x}_i}. \quad (11)$$

The TKE equation (10) can now be integrated in the bed-normal direction ($\tilde{z}$) to get the global balance.

$$\tilde{\Phi} - \tilde{\epsilon} + \frac{1}{Re_r} \left\{ \left[ \frac{d\tilde{k}}{d\tilde{z}} \right]_0^{\tilde{h}} + R_{t, \tilde{V}_c} \tilde{\zeta} \right\} = \beta + \gamma R_{t, \tilde{V}_c} \tilde{V}_c$$

(12)

where

$$\tilde{\Phi} = \int_{0}^{\tilde{h}} \tilde{\Phi} d\tilde{z}, \quad \tilde{\epsilon} = \int_{0}^{\tilde{h}} \tilde{\epsilon} d\tilde{z}, \quad \beta = -\gamma \int_{0}^{\tilde{h}} \tilde{u}'\tilde{v}' d\tilde{z}, \quad \text{and} \quad \tilde{\zeta} = \frac{\tilde{c}_{eb} - \tilde{c}_{ct}}{Pe_r/Re_r}.$$

Terms on the right hand side of (12) quantify turbulence damping due to suspended sediments. As expected, the turbulence damping effects are only due to sediments. Table 2 presents the TKE budget of cases that are closest to the critical turbulence damping limit for each of the sets A, B and C. Also presented in the table is the TKE budget of case 5 from [2]. Case 5 represents the critical turbulence damping limit for turbidity currents solely driven by a mono disperse mixture of sediment. Notice that the TKE budget of all the cases show striking agreement. This means that at the critical state the bulk TKE production ($\tilde{\Phi}$), bulk TKE dissipation ($\tilde{\epsilon}$) and bulk TKE damping terms $\beta$ and $\gamma R_{t, \tilde{V}_c} \tilde{V}_c$ are insensitive to the composition of the mixture. Furthermore, an effective settling velocity $\tilde{V}_{eff} = \gamma \tilde{V}_c$ can be defined for cases 6A, 6B, 6C and this value closely matches with the mono disperse turbidity current case 5. From these observations it can be concluded that the criteria for complete turbulence suppression for currents driven by mono disperse suspensions holds for sediment-laden saline currents. An implication of this is that the scaling relations for the turbulence suppression criteria developed in Cantero et al.[1] should also hold for sediment-laden saline currents

$$R_{t, \tilde{V}_{eff}, \tilde{z}, crit} = 0.041 \ln(Re_r) + 0.11 \quad (13)$$

Table 2. Turbulent kinetic energy budget for all the critical cases from the present study.

| case | $|\tilde{V}|$ | $\gamma_s$ | $\tilde{\Phi}$ | $\tilde{\epsilon}$ | $\beta$ | $R_{t, \gamma} \tilde{V}_c$ | $R_{t, \zeta}/Re_r$ | $\gamma \tilde{V}_c$ |
|------|------------|----------|--------------|---------------|-------|----------------|----------------|-------------|
| 6A   | 0.0275     | 0.04     | 6.534        | 6.179         | 0.113 | 0.302          | 0.0978         | 0.0264      |
| 6B   | 0.035      | 0.24     | 6.598        | 6.237         | 0.117 | 0.304          | 0.0977         | 0.0266      |
| 6C   | 0.05       | 0.469    | 6.516        | 6.162         | 0.113 | 0.303          | 0.1019         | 0.0266      |
| 5    | 0.026      | 1.0      | 6.590        | 6.230         | 0.117 | 0.296          | 0.0958         | 0.0260      |

5. Conclusion and discussion

The present work extends the results of Cantero et al.[1] and Shringarpure et al.[2] to the cases of sediment-laden saline currents where the forcing is done by salinity and suspended sediments. Our DNS results show that by
increasing the forcing by salinity the flow can be held in a turbulent state where it is able to maintain large sediments in suspension. Large sediments refer to sediments that would not be able to sustain the flow by themselves. The DNS results also show that the transition to total turbulence suppression is abrupt with changes of the total sediment load (γ).

Salinity can be also interpreted as a fraction of sediment that is fine enough that its settling velocity is negligible. Thus, the case of sediment-laden saline currents is a simplified bi-disperse model where the fine sediments do not settle. Our results thus show that turbidity currents could transport coarse sediments in suspension as long as the mixture has sufficient quantity of fine sediments to sustain turbulence. This is the underlying mechanism by which real turbidity currents derive their ability to transport in suspension large/heavy sediments for long distances.

The turbulence suppression criteria proposed by Cantero et al.[1] has been extended to the case of sediment-laden saline currents. The original criteria can be directly applied to the flows studied in this work by employing an effective settling velocity $\tilde{V}_{\text{eff}} = \gamma \tilde{V}$.

References