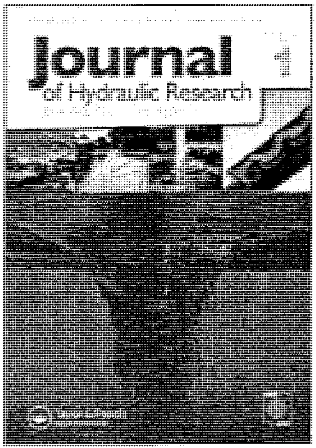

Journal of Hydraulic Research
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t916282780

The effect of turbulence on sediment deposition

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Online publication date: 13 January 2010

To cite this Article Hoyal, D. C. J. D. , Atkinson, J. F. , Depinto, J. V. and Taylor, S. W.(1995) 'The effect of turbulence on sediment deposition', Journal of Hydraulic Research, 33: 3, 349 — 360
To link to this Article: DOI: 10.1080/00221689509498576
URL: http://dx.doi.org/10.1080/00221689509498576

The effect of turbulence on sediment deposition

Influence de la turbulence sur le dépôt des sédiments

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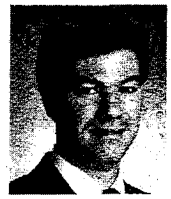

ABSTRACT

A Lagrangian (random walk) sediment deposition model is used to investigate the competing effects of gravity and turbulence on deposition to a fully absorbing bed. This approach permits an analysis of the probability density function of deposition velocity as well as its mean. A distinct change in transport behavior is observed at a critical value of $w^*_c = w_s/U^* = 0.1$, where w_s is the fall velocity in still fluid and U^* is the shear velocity. Turbulence controls the transport of particles below w^*_c which deposit faster than similar particles in still water. For particles above w^*_c, the still water fall velocity is a good estimate of the mean deposition velocity. A discrepancy between the Lagrangian model results and experimental data (for $w^* < w^*_c$) may suggest that existing diffusion models are an incomplete representation of the physical system. An alternative conceptual model is suggested, based on coherent intermittent turbulence structures, which appears to explain the experimental results more effectively. Many natural and engineered sedimentation systems have $w^* < w^*_c$ and are dominated by turbulent sediment transport. New sediment removal technologies are suggested based on turbulence enhanced deposition.

RÉSUMÉ

Un modèle lagrangien de dépôt des sédiments a été utilisé pour étudier l'antagonisme entre gravité et turbulence sur le processus de dépôt sur un lit totalement absorbant. Cette approche permet l'analyse de la densité de probabilité de la vitesse de dépôt aussi bien que de sa moyenne. Un changement significatif dans le processus de transport est observé pour une valeur critique de $w^*_c = w_s/U^* = 0.1$, expression dans laquelle w_s est la vitesse de chute de la loi de Stokes en eau calme et U^* la vitesse de cisaillement. La turbulence régit le transport des particules endessous de la valeur critique w^*_c qui donne un dépôt plus rapide que la loi de Stokes. Pour des particules au-delà du seuil w^*_c, la loi de Stikes représente une bonne estimation de la vitesse moyenne de dépôt. La divergence entre les résultats du modèle lagrangien et les valeurs expérimentales (pour $w^* < w^*_c$) laisse à penser que les modèles de diffusion existants représentent imparfaitement le processus physique. Un nouveau modèle conceptuel est présenté, basé sur la notion de structures de turbulence intermittentes cohérentes, qui explique mieux les résultats expérimentaux. Beaucoup de systèmes de sédimentation naturels ou élaborés par l'homme, sont caractérisés par $w^* < w^*_c$ et sont essentiellement dans le domaine du transport sédimentaire turbulent. De nouvelles stratégies d'elimination des particules sédimentaires sont proposées, basées sur le dépôt grâce à un renforcement de la turbulence.

Revision received February 28. Open for discussion till December 31, 1995.

1 Introduction

The deposition of solids from water is of importance in many engineering applications including: water treatment, reservoir sedimentation, hydroelectric dams, canals, and river/coastal navigation. Sediment deposition models in their simplest form consider transport to a bed with no re-suspension (i.e., fully absorbing). This boundary condition is based on the assumption that particles enter a near-stationary layer adjacent to the bed where upward turbulent velocities are of insufficient magnitude to overcome gravity settling (assuming that the particles are smaller than the thickness of the layer). A fully absorbing boundary condition in a sediment deposition model has the effect of instantaneously absorbing all particles which reach a specified elevation above the bed.

As particles approach neutral buoyancy in a turbulent fluid, transport to a fully absorbing boundary by turbulent diffusion can exceed transport by gravitational settling. This is true even for a symmetrical distribution of the turbulent fluctuating velocities (zero mean) since particles at the limit (i.e., neutrally buoyant) must diffuse faster than they settle. This enhanced turbulent deposition process (driven by the absorbing boundary) must produce a positive gradient (i.e., concentration increases with height) although the strong mixing capacity of turbulence leads to concentration profiles not significantly different from uniform in this study. At the other extreme turbulent fluctuations are expected to have a negligible effect on large and, or heavy particles which settle at their still water fall velocity. Experiments and models are necessary to understand deposition between these two extremes. A useful parameter in this range is $w_s h/2\varepsilon$ (where w_s is the Stokes' fall velocity in still fluid, h is the depth, and ε is the sediment diffusion coefficient) which represents the ratio of a characteristic rate for settling $[w_s/h]$ to a characteristic rate for turbulent diffusion $[2\varepsilon/h^2]$ (Lick, 1982). This variable ($w_s h/2\varepsilon$) is equivalent to w_s/U^*, (where U^* is the shear velocity) if the common assumption is made that $2\varepsilon/h$ is a good approximation to U^*. Both $w_s h/2\varepsilon$ and w_s/U^* will be denoted as w^* in this paper.

The mean deposition velocity of a group of particles to the bed, (w_d), includes the combined effect of all transport processes and is not necessarily the same as the settling velocity in still water. Models developed to determine the deposition velocity usually include a highly averaged representation of the turbulent velocity field defined by a characteristic scale at any height. There are two possible approaches for modeling particle transport in turbulence, Eulerian and Lagrangian. The Eulerian models (e.g., Dobbins, 1944; Sarikaya, 1977) solve the time averaged advection-diffusion equation in various forms. In one dimension (vertical) the equation reduces to

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial y}\left(\varepsilon\frac{\partial C}{\partial y}\right) + w_s\frac{\partial C}{\partial y} \tag{1}$$

where C is the sediment concentration, ε is the sediment diffusion coefficient and y is the vertical coordinate (positive upwards). An alternative method, the Lagrangian random walk, traces the trajectory of individual particles in a turbulent velocity field over time, where turbulent velocities are realizations of a random process. Random walk studies include Bayazit (1971, 1972), Li and Shen (1975) and Bechteler and Farber (1980, 1982, 1983, 1985The random walk approach was selected for this study because it generates distributions of transport statistics rather than average values and allows a more natural implementation of boundary conditions.

The aim of this paper is to characterize deposition from an idealized turbulent velocity field with depth dependant mixing coefficient (i.e., shear turbulence) to a fully absorbing boundary. Comparing this ideal case with experimental data can illuminate what we do, and do not, understand about the sediment deposition process. The model and model results are presented in Sections 2 and 3.

Generally, experimental data indicate a link between w_d and w_s which is not demonstrated by the Lagrangian model results and this discrepancy is explained in terms of intermittent coherent turbulence structures generated near the bed (Section 4). A comparison of model results and experimental data indicates that turbulence enhanced deposition may be possible over a small range of w^* and potential applications of turbulence enhanced deposition to engineered systems are presented in Section 5.

2 The model

The two dimensional random walk model selected for this study was first developed by Li and Shen (1975) and later analyzed by Bechteler and Farber (1980). The model simulates deposition in clear fluid (i.e., no particle-particle interaction) to a fully absorbing bed. Only the working model equations are presented here. A detailed derivation of the model equations and discussion of the assumptions are presented by Li and Shen (1975).

Particle movement is controlled by the equations

$$\Delta Y_i = (v' - w_s)\,\Delta t_i \tag{2}$$

$$\Delta X_i = (u(y) - u')\,\Delta t_i \tag{3}$$

where ΔY_i and ΔX_i are the i^{th} particle displacements, v' and u' are the random components of velocity, w_s and $u(y)$ the mean advective velocities in the vertical and horizontal directions respectively, and Δt_i is the time increment. A logarithmic profile is assumed to correlate the mean velocity with distance above the bed. A hydraulically rough boundary is assumed,

$$\frac{u(y)}{U^*} = 8.5 + 2.5\ \ln\frac{y}{k_s} \tag{4}$$

where k_s is height of the roughness elements. Particles are fully reflected at the water surface and instantaneously absorbed once they reach the elevation of k_s.

It is assumed that both the streamwise (u') and cross-streamwise fluctuating velocities (v') are normally distributed. The covariance of u' and v', $E[u'v']$ is calculated by a simplified Reynolds equation (McQuivey and Richardson, 1969)

$$E[u'v'] = v\frac{u^*}{ky} - u^{*2}\left(l - \frac{y}{h}\right) \tag{5}$$

in which v is kinematic viscosity, h is the total depth, and $\kappa = 0.4$ is assumed. By definition the correlation coefficient (ρ) of u' and v' is:

$$\rho = \frac{E[u'v']}{\sigma_{u'}\sigma_{v'}} \tag{6}$$

where $\sigma_{u'}$ and $\sigma_{v'}$ are the standard deviations of horizontal and vertical turbulent fluctuating velocities respectively. Experimental results obtained by Rechardt (1938), McQuivey and Richardson (1972), and Laufer (1954) indicate that the correlation coefficient ρ is approximately equal to a constant r for some distance above the bed and drops to zero at the free surface, i.e.,

$$\rho = r \text{ for } 0 < \frac{y_i}{h} \leq 0.5$$
$$\rho = 2r\left(1 - \frac{y_i}{h}\right) \text{ for } 0.5 < \frac{y_i}{h} \leq 1.0 \quad (7)$$

McQuivey and Richardson (1972) reported that r is about –0.7 for flow over rough boundaries and –0.4 for flow over a smooth boundary. The value of $\sigma_{u'}$ is related to $\sigma_{v'}$ by a constant c so that

$$\sigma_{v'} = c \cdot \sigma_{u'} \quad (8)$$

From actual measurements McQuivey and Richardson (1972) found that c was about 0.5 for a rough boundary and 0.7 for a smooth boundary. Thus $\sigma_{u'}$ can be calculated from

$$\sigma_{u'} = \sqrt{\frac{E[u'v']}{c \cdot \rho}} \quad (9)$$

and the value for $\sigma_{v'}$ may then be calculated from equation (8).

The time step is calculated by setting the expectation of vertical particle movement $E[|V_i - w_i|]$ equal to the Eulerian length scale, $l(y_i)$, at that depth:

$$\Delta t_i = \frac{l(y_i)}{E[|V_i - w_i|]} \quad (10)$$

where $E[|V_i - w_i|]$ is calculated from

$$E[|V_i - w_i|] = w_s + \sigma_{v'}\sqrt{\frac{2}{\pi}}\exp\left[-\frac{1}{2}\left(\frac{w_s}{\sigma_{v'}}\right)^2\right] \quad (11)$$

The approximations to the Eulerian length scale given by Sullivan (1971) are:

$$l(y_i) = 0.21h \text{ for } 0.5 < \frac{y_i}{h} \leq 1$$
$$l(y_i) = 0.42y_i \text{ for } 0 < \frac{y_i}{h} \leq 0.5 \quad (12)$$

Numerical experiments were run for a number of initial particle source profiles representing extreme examples of natural profiles. Source concentration profiles included uniform, surface point, and "slugs" (i.e., uniform distribution over a restricted range of y). Slug profiles were implemented at three heights, top (y/h = 0.8 – 1.0), middle (y/h = 0.4 – 0.6) and bottom (y/h = 0 – 0.2). A wide range of input parameters was selected in order to cover the full spectrum of vertical transport behavior. Values of input parameters were: U^* (0.1 – 10 cm/sec), w_s (0.0001 – 10 cm/sec), h (10 – 1000 cm), k_s (0.05 cm). This represents a much wider range of w^* than considered in previous modeling exercises (e.g., Li and Shen, 1975; Bayazit, 1971), which were restricted to a range of w^* where gravity dominates. A statistically significant number of random walkers (i.e., 1000) were simulated for each w_s, U^*, h combination. Deposition velocity (V) was calculated for each particle using the equation

$$V = \frac{D}{T} \quad (13)$$

where D is the vertical distance traveled by the particle and T is the time elapsed until the particle is absorbed at the bed. The model output was analyzed to determine the effect of turbulence on the probability density function (*PDF*) of *V*, including: arithmetic average (VS), standard deviation SD[*V*], skewness (*sk*) and kurtosis (*ku*).

3 Model results

Deposition velocity statistics presented in Figure 1 include: (a) VS, (b) SD[*V*], (c) *sk* and (d) *ku* as a function of w^* for two values of U^* (0.1, 1 cm/sec). Top, middle and bottom slugs are represented by solid, dashed and dotted lines respectively. The close proximity of the VS curves indicates that the mean deposition velocity in turbulence is predominantly independent of the initial concentration distribution. The results for the surface point and uniform initial concentration profiles are not presented but lie very close to the middle slug, and top slug respectively.

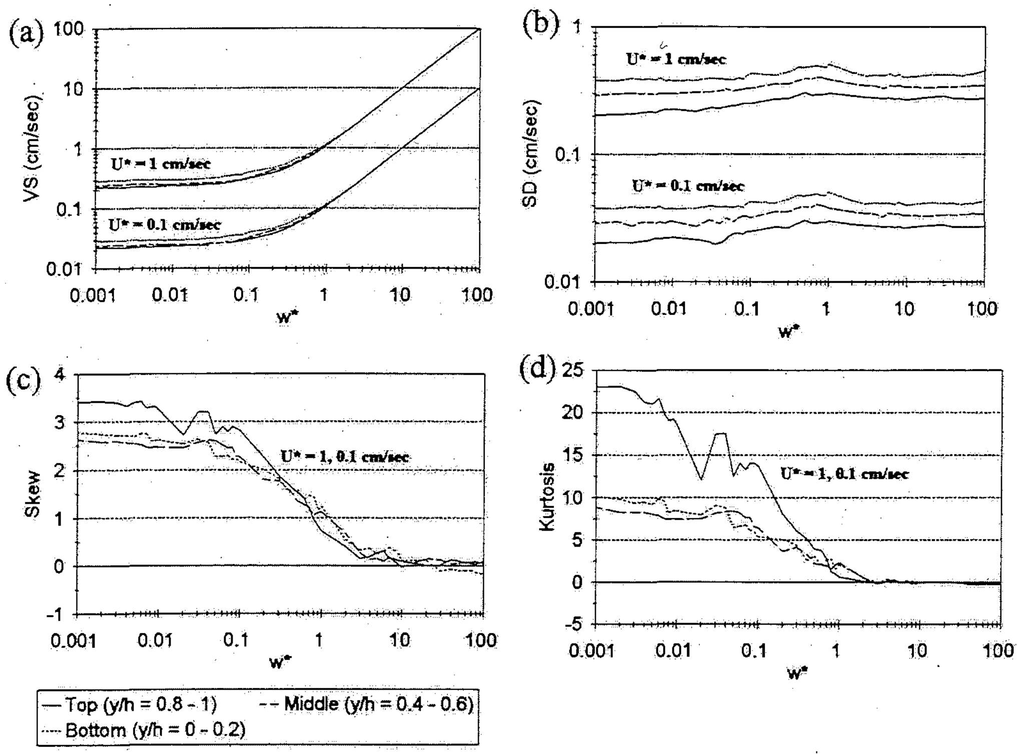

Fig. 1. (a) VS cm/sec, (b) SD[*V*] cm/sec, (c) *sk* and (d) *ku* as a function w^* and U^* for three slug initial concentration profiles, Top ($y/h = 0.8 - 1.0$), Middle ($y/h = 0.4 - 0.6$) and Bottom ($y/h = 0 - 0.2$).

The trends of VS illustrate that the transport behavior predicted theoretically at the limits of large or small w^* are valid for most of the sediment-turbulence spectrum. Particle transport is either dominated by gravity, in which case VS agrees very closely with w_s (because large particles are not significantly affected by the turbulent velocity fluctuations) or by turbulence where VS is a function of U^* and particles diffuse at the same rate as fluid momentum. The transition region between these two modes of transport is narrow (i.e., the region where both turbulent diffusion and gravity affect transport). A critical value of $w^*(w^*_c) = 0.1$ is selected to approximate the transition between gravity and turbulence dominant transport. Results can be summarized as follows: If $w^* > w^*_c \Rightarrow VS(w_s) = w_s$; if $w^* < w^*_c \Rightarrow VS(U^*) > w_s$.

Incorporating all of the simulation data presented in Figure 1, Figure 2 illustrates that just below w^*_c, VS may drastically exceed w_s. The fact that all the VS curves of Figure 1a collapse into one curve for $w^* < w^*_c$ on Figure 2 indicates that below the threshold the deposition velocity is functionally dependent on the turbulence intensity (U^*) only. Calculated values of w^* from the literature indicate that turbulence dominates vertical sediment transport in many natural and engineered sedimentation systems (i.e., $w^* < w^*_c$). Typical values of w^* are presented for sedimentation basins (Table 1) and rivers (Table 2). Table cells below the heavy line indicate $w^* < w^*_c$.

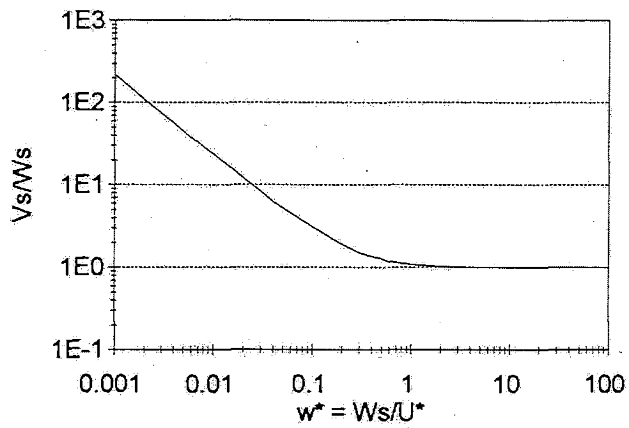

Fig. 2. Mean deposition velocity (VS) / Stokes' velocity (w_s) as a function of w^* for surface point source.

The standard deviation (SD[V]) (Figure 1, (b)) of deposition velocity is also strongly dependent on U^* and varies little between the three source profiles. SD[V] is dependent on w^* for $w^* > w^*_c$ but less so than VS. Rather surprisingly, the results show that SD[V] is slightly greater for larger w^*. This result is unexpected and may be due to the change in shape of PDF's as turbulence dominates. The skewness and kurtosis statistics presented in part (c) and (d) of Figure 1 are interesting since they demonstrate that the shape of the distributions is independent of U^* (i.e., the curves for $U^* = 0.1$ cm/sec and 1.0 cm/sec fall on top of each other). These statistics indicate that an asymptotic lognormal distribution is approached as w^* gets smaller and that the shape of this distribution is independent of the level of turbulence. Typical V distributions are presented in Figure 3. The asymptotic distribution represents the deposition velocity PDF for neutrally buoyant particles released from a particular initial concentration profile. As w^* is lowered the shape of the distributions grades from normal ($sk \approx 0$) for large w^* to the asymptotic distribution which approaches lognormal ($sk \approx 3$). The separation of the skewness and kurtosis curves for $w^* < w^*_c$ indicates that the asymptotic shape of the V distribution for $w^* < w^*_c$ is strongly dependent on initial concentration source. This result is to be expected since the source condition will control the subset of velocities experienced by the particles.

Table 1. Typical values of w^* for sedimentation basins.

Typical floc specific gravity = 1.10 (Camp, 1946)			Hypothetical Sedimentation Basins		Radial Flow Circular# U_0=0.57cm/s D=437 cm	Wide Rectangular# U_0=1.6 cm/s D=569.8 cm	Narrow Rectangular# U_0=2.6 cm/s D=431.2 cm
		U* (cm/sec) =	0.0001	0.001	0.0215	0.059	0.1003
SEDIMENT GRADE	MAXIMUM SIZE (μm)	Stokes Law Fall Velocity (cm/sec)	w_s/U^*	w_s/U^*	w_s/U^*	w_s/U^*	w_s/U^*
Fine Sand	250	3.04×10^{-1}	3.04×10^{3}	3.04×10^{2}	1.45×10^{1}	5.15×10^{0}	3.03×10^{0}
Very Fine Sand	125	7.60×10^{-2}	7.6×10^{2}	7.60×10^{1}	3.62×10^{0}	1.29×10^{0}	7.57×10^{-1}
Coarse Silt	62	1.87×10^{-2}	1.87×10^{2}	1.87×10^{1}	8.9×10^{-1}	3.17×10^{-1}	1.86×10^{-1}
Medium Silt	31	4.67×10^{-3}	4.67×10^{1}	4.67×10^{0}	2.22×10^{-1}	7.92×10^{-2}	4.66×10^{-2}
Fine Silt	16	1.24×10^{-3}	1.24×10^{1}	1.24×10^{0}	5.93×10^{-2}	2.11×10^{-2}	1.24×10^{-2}
Very Fine Silt	8	3.11×10^{-4}	3.11×10^{0}	3.11×10^{-1}	1.48×10^{-2}	5.27×10^{-3}	3.10×10^{-3}
Coarse Clay	4	7.78×10^{-5}	7.78×10^{-1}	7.78×10^{-2}	3.70×10^{-3}	1.32×10^{-3}	7.75×10^{-4}
Medium Clay	2	1.94×10^{-5}	1.94×10^{-1}	1.94×10^{-2}	9.26×10^{-4}	3.30×10^{-4}	1.94×10^{-4}
Fine Clay	1	4.86×10^{-6}	4.68×10^{-2}	4.86×10^{-3}	2.31×10^{-4}	8.24×10^{-5}	4.85×10^{-5}
Very Fine Clay	0.5	1.22×10^{-6}	1.22×10^{-2}	1.22×10^{-3}	5.79×10^{-5}	2.06×10^{-5}	1.21×10^{-5}

*Shear velocities calculated from depth integrated velocity profile, U_0= mean velocity, D = depth
Data from Camp (1946) Table 2, p. 933.

Table 2. Typical values of w^* for rivers.

Solid particles assumed, specific gravity = 2.65			Missouri R.	Chicago Ship Canal	Derwent River	Sacramento River
		U* (cm/sec) =	7.4	1.91	14.0	5.1
SEDIMENT GRADE	MAXIMUM SIZE (μm)	Stokes Law Fall Velocity (cm/sec)	w_s/U^*	w_s/U^*	w_s/U^*	w_s/U^*
Fine Sand	250	5.01	6.77×10^{-1}	2.62	3.58×10^{-1}	9.83×10^{-1}
Very Fine Sand	125	1.25	1.69×10^{-1}	6.56×10^{-1}	8.95×10^{-2}	2.46×10^{-1}
Coarse Silt	62	3.08×10^{-1}	4.17×10^{-2}	1.61×10^{-1}	2.20×10^{-2}	6.05×10^{-2}
Medium Silt	31	7.71×10^{-2}	1.04×10^{-2}	4.04×10^{-2}	5.51×10^{-3}	1.51×10^{-2}
Fine Silt	16	2.05×10^{-2}	2.77×10^{-3}	1.08×10^{-2}	1.47×10^{-3}	4.03×10^{-3}
Very Fine Silt	8	$5.13 \times 10^{3-}$	6.94×10^{-4}	2.69×10^{-3}	3.67×10^{-4}	1.01×10^{-3}
Coarse Clay	4	1.28×10^{-3}	1.73×10^{-4}	6.72×10^{-4}	9.17×10^{-5}	2.52×10^{-4}
Medium Clay	2	3.21×10^{-4}	4.43×10^{-5}	1.68×10^{-4}	2.29×10^{-5}	6.29×10^{-5}
Fine Clay	1	8.02×10^{-5}	1.08×10^{-5}	4.20×10^{-5}	5.73×10^{-6}	1.57×10^{-5}
Very Fine Clay	0.5	2.01×10^{-5}	2.71×10^{-6}	1.05×10^{-5}	1.43×10^{-6}	3.93×10^{-6}

*River shear velocities from Fisher et al., (1979) Table 1 & 2, p. 43

The type of particle transport behavior in turbulence (i.e., whether gravity or turbulence dominated) is illustrated very well by the evolution of concentration profiles in the flow (Figure 4). These concentration profiles were created for the top slug initial profile by plotting the vertical position of all particles at a particular elapsed time as a relative frequency histogram. For $w^* > w^*_c$ the slug clearly retains its form until it is absorbed at the bottom. For $w^* < w^*_c$ any trace of the original slug soon vanishes and a strong tendency exists for material to smear into a uniform distribution. These observations are in agreement with the fact that in the range of w^* where turbulence enhanced deposition dominates, the distribution of sediment predicted by a Rouse type formula is nearly uniform. Consequently, significantly positive concentration profiles never form.

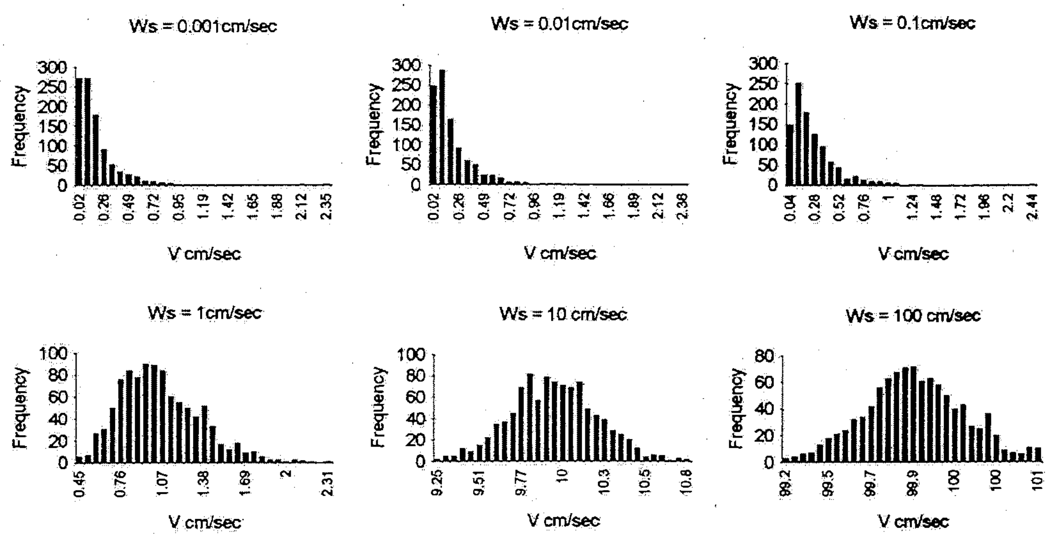

Fig. 3. V histograms, $U^* = 1$ cm/sec, surface point source.

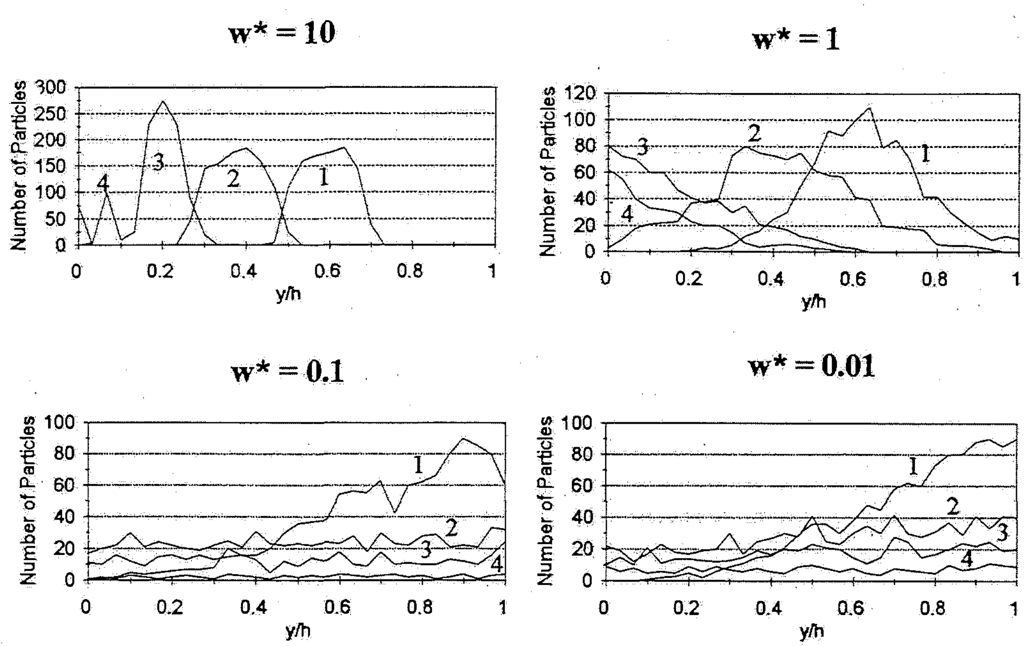

Fig. 4. Concentration profiles from the top slug source profile ($y/h = 0.8 - 1.0$), $w^* = 10, 1, 0.1, 0.01$, $U^* = 1$ cm/sec, curves 1, 2, 3, 4 illustrate the time development of profiles.

4 Comparing the model results and experimental trends

The deposition behavior exhibited by the Lagrangian model is not in agreement with general experimental trends for $w^* < w^*_c$. Experimental data, (e.g., Reynolds, 1990) usually indicate that deposition occurs at a rate close to w_s and is retarded as turbulence increases. This divergence between the model and data may suggest that our present conceptualization of the deposition process is incomplete. The Lagrangian model, like most other sediment deposition models, is based on a highly averaged turbulent velocity field and near-bottom quiescent layer which absorbs all particles. The absorbing bottom layer assumption seems well supported experimentally, since many studies, e.g., Reynolds (1990) show that deposited sediment is not resuspended (so long as the flow conditions remain constant). Consequently, the experimentally observed link between w_d and w_s may be attributable to some feature of the turbulent velocity field that has been averaged out.

Structured intermittent eddies near the bed appear to be a good candidate for this deposition inhibiting process. Recent investigations (see Robinson (1991) for a comprehensive review) have revealed that shear turbulence is structured in the near wall region into rapid short duration inflow (sweeps) and slower long duration outflow (bursts), intermittent but persistent in time. These structures are difficult to include in a traditional diffusion model, either Lagrangian or Eulerian, which assumes a single characteristic turbulence scale at any particular depth.

Bagnold (1966) introduced the notion that skewness of the vertical velocity fluctuations maintains sediment in suspension. This skewness has been observed in detailed experimental measurements of turbulent velocity fields, (e.g., Wei and Willmarth, 1991) and is attributed to the bursting phenomenon. The addition of skewed v' velocity fluctuations to the Lagrangian model would appear to violate the principle of fluid continuity. Continuity could be maintained by associating the upwards and downwards velocity fluctuations with separate time-scale distributions each with a different mean. However, this approach would be difficult to implement in the existing Lagrangian model structure. If continuity is maintained, it seems that the transfer of particles up and down through a plane above the bed should remain approximately equal so long as the fluid velocity in the eddies exceeds w_s (i.e., w^* locally less than w^*_c).

The idea, that intermittent coherent structures may control turbulent deposition rates, can be illustrated by separating the near bed region into two layers, lying below a well mixed region. A lower layer adjacent to the bed, the permanently stationary layer (PSL) from which deposited sediment cannot be re-entrained, and an overlying intermittently stationary layer (ISL), mixed by turbulent ejection events. The top of the upper layer (ISL) may be defined by the level at which w_s = RMS (v'). Sediment moved into the ISL from above will settle by gravity in the quiescent intervals between intermittent coherent turbulence events and, if not ejected, will be deposited in the PSL. The residence time of a particle in the ISL, i.e., its susceptibility to continual re-suspension is related to its gravity settling velocity, w_s, explaining the link between w_s and w_d observed in the experimental data.

The scarcity of experimental evidence indicting enhanced deposition by turbulence, (i.e., $w_d > w_s$), so common in the Lagrangian model results, may be due to the lack of any mechanism for the transfer of particles from the turbulent fluid to the PSL. A prerequisite for turbulent deposition is the ability of a particle to cross fluid trajectories. Enhanced turbulent deposition, if it exists, may be limited to a narrow range around w^*_c where particle transport is turbulence dominated but particle inertia allows particles to cross fluid trajectories. Above this range of w^*, particles move downwards by gravity settling, while below this range particle inertia is not important and particles diffuse in a similar manner to fluid elements.

Of the available experimental data only one study appears to support this idea of enhanced (inertial) turbulent deposition. Jobson and Sayre (1970), in an extensive study of the vertical transfer of "heavy" particles in open channel flow, measured the deposition rate of fine and coarse sand in a recirculating 200 ft rectangular flume. Experimental conditions are described in detail in Jobson (1968) and Jobson and Sayre (1970). Although a fully absorbing boundary was not enforced experimentally, measured average deposition velocities greater than w_s indicate that transport to the bed was promoted by turbulence (i.e., that the bed was at least partially absorbing for turbulently transported sediment). The bed of the flume was lined with 1–1 1/16 inch high wooden cleats to increase hydraulic roughness which may have had a trapping effect on sediment near the bed. Mean deposition velocities for fine sand ($w^* = 0.6, 0.1$) calculated from integrated vertical concentration profiles were approximately 40% and 65% greater than w_s. Actual deposition velocities may have been even greater since they noticed that some of the fine sediment was transported after being deposited. These authors originally ascribed this result to the grouping of sediment upon release from the injection system. However, an experiment involving tagged individual sediment grains (coarse sand) showed that only 1.5 % of the difference between w_s and w_d could be attributed to grouping. The experiment of Jobson and Sayre was not simulated directly because of the difficulty of including inertial effects within the kinematic random walk modeling framework. However, this experiment appears to qualitatively support the idea of turbulent enhanced deposition restricted to a narrow range of w^* where particle and fluid element trajectories cross, but turbulence enhances the transport rate.

5 Potential applications

The model results and physical arguments presented in this paper indicate that there may be some potential for engineering improved particle removal from turbulent water. The results of Jobson and Sayre (1970) and related discussion presented in Section 4, suggest that turbulent enhanced deposition may be possible in a small window of w^* around w^*_c. In engineered systems the w^* value can be controlled by adjusting the intensity of turbulence (U^*).

Apparently, sediment particles arrive near the solid boundary at a rate faster than Stokes' law. If some deposition mechanism could be implemented technologically, faster (turbulent) deposition rates might be realized. Potential technologies may include:

1. Blocks or trapping structures on the bed (i.e., similar to Jobson and Sayre's roughness cleats);
2. Use of bristles or fibrous surfaces to trap particles;
3. Using a polarized electric field to drag charged particles (e.g., clays) across the innermost region of the viscous sublayer.

Increasing the turbulence and reducing the depth of the flow could improve efficiency up to the technological limit of the removal process. This type of removal may be most practical for solid discrete sediment particles, since in cohesive sediments, flocs are broken up with increasing turbulence.

6 Summary and conclusions

The Lagrangian study of deposition to a fully absorbing boundary presented in this paper extends earlier work by considering a larger range of deposition behavior (w^* values) than previous studies. The stochastic approach permits a detailed study of the deposition velocity PDF and associated moments over the transition from gravity to turbulent dominant deposition. Results demonstrate that while the deposition velocity is a strong function of turbulence intensity (U^*) for $w^* < w^*_c$ the shape of the distributions is independent of turbulence intensity and depends on w^* and the initial concentration distribution only. The region where both gravitational settling and turbulent diffusion control vertical transport is narrow, and can be defined (approximately) by a single value of w^*, i.e. $w^*_c = 0.1$. Sediment with $w^* > w^*_c$ is dominated by gravity and on average will settle at Stokes' law. Sediment with $w^* < w^*_c$ is dominated by turbulence and on average, will settle faster than predicted by Stokes' law.

Fundamental to this study is the assumption of a fully absorbing boundary, whereby all sediment that enters a region very close to the bed is deposited. Apparently this assumption is reasonable for "heavy" particles, since we know that turbulence scales must go to zero at the boundary. Arguments developed in this paper suggest that the common diffusion models of sediment deposition which assume a characteristic scale of turbulence at any elevation may be unable to accurately predict sediment deposition rates. An alternative conceptual model based on intermittent turbulence structures appears to explain the common experimental link between w_s and w_d more effectively and might provide the basis for improved mathematical models of sediment deposition. Experimental data suggest that an enhanced turbulent deposition effect does appear to exist over a restricted range of w^* and this phenomenon might provide the basis for improved removal in engineered sedimentation systems. Enhanced deposition of sediment in turbulent water appears to warrant further investigation.

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List of symbols

ε	Sediment Diffusion Coefficient
υ	Kinematic Viscosity
ρ	Correlation coefficient between u' and v'
$\sigma_{v'}$	Standard deviation of the turbulent velocity distribution in the cross streamwise direction
$\sigma_{u'}$	Standard deviation of the turbulent velocity distribution in the streamwise direction
C	Concentration of suspended solids
c	Constant, ratio between $\sigma_{v'}$ and $\sigma_{u'}$
C_0	Initial sediment concentration
D	Vertical distance traveled by particle from release until absorbtion at bed
$E[.]$	Expectation
h	Total depth
κ	Von Karman's universal constant
k_s	Height of the roughness element
$L(y_i)$	Local Eulerian length scale
p	Deposition probability
$P(.)$	Probability density function
r	Constant
RMS	Root mean square
SD	Standard Deviation
Δt_i	Time increment at i^{th} step
T	Time until particle is absorbed at bed
u'	Random velocity component in the streamwise direction
U^*	Shear Velocity
U	Mean Flow velocity (depth integrated)
$u(y)$	Mean streamwise velocity at y
v'	Random velocity component in the cross-streamwise direction
V	Average downwards velocity of the particle, ($V = D/T$)
VS	Arithmetic mean of V for n random walks
w_s	Quiescent settling velocity from Stokes' law
w_d	Deposition velocity
w^*	w_s/U^*
w^*_c	Critical value of w^* for gravity-turbulence
$\Delta x_i, \Delta y_i$	Increment of particle movement at i^{th} step
y	Vertical axis