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SUSPENDED SEDIMENT EFFECT ON TURBULENT DIFFUSION

by

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MANAGEMENT PERSPECTIVE

When an open-channel flow carries sediment in suspension, its flow characteristics are different from a similar flow which carries no sediment.

This report demonstrates for the first time, that the mixing characteristics are different. It shows that the rate at which a pollutant diffuses can be significantly reduced when the concentration of suspended sediments is large.

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PERSPECTIVE-GESTION

Le régime d'un écoulement à surface libre qui transporte des sédiments en suspension diffère du régime d'un écoulement semblable mais qui ne charrie pas de sédiments.

Ce rapport démontre pour la première fois que les caractéristiques du mélange sont différentes. On y explique que la vitesse de diffusion de polluants peut être considérablement réduite lorsque la concentration des sédiments en suspension est élevée.

Chef intérimaire
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SOMMAIRE : On a fait des expériences afin d'étudier l'effet des sédiments en suspension sur la diffusion de contaminants passifs issus d'une source linéaire dans des écoulements à surface libre. En général, on a constaté peu d'effets sur la vitesse limite du régime turbulent; cependant, l'échelle de longueur intégrale et la diffusibilité du régime turbulent ont été réduites de 73 p. 100 et 69 p. 100 dans des écoulements dont les concentrations moyennes de sédiments par volume étaient respectivement de $3,8 \times 10^{-4}$ et $1,9 \times 10^{-3}$.

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SUMMARY: Experiments were conducted to study the effect of suspended sediments on the diffusion of a line source of scalar contaminant in open-channel flows. While turbulent velocity was relatively unaffected, the reduction in integral length scale and turbulent diffusivity were 73% and 69% for flows with average sediment concentrations by volume of 3.8×10^{-4} and 1.9×10^{-3} respectively.

INTRODUCTION

The presence of suspended sediments in an open-channel affects the velocity distribution of the flow. It has been shown by Coleman (1) that as the concentration of suspended sediment increases, the velocity profile outside of the wall layer deviates more and more from the logarithmic velocity distribution. Using the evidence presented by Coleman, Lau (4) has shown that the flow resistance must be reduced by the presence of suspended sediments.

Given the effects on the velocity distribution and flow resistance, it is quite obvious that the eddy viscosity of the flow will also be affected. Although no concrete evidence has been put forward, various authors have argued that suspended sediments can cause a "damping" effect of the turbulence in the fluid (2,7,8). It follows then that the presence of suspended sediments will affect the turbulent diffusion and will alter the rate of spreading of contaminant in open channel flows. However, there appears to be very little information on this subject. Therefore a set of experiments was conducted to investigate if this effect does exist.

EFFECTS ON THE EDDY VISCOSITY

The effects of suspended sediments on the eddy viscosity distribution can be deduced from the evidence given by Coleman (1). It was shown that the changes brought about by the sediment concentration can be account for by a change in the wake-strength parameter in the equation for the velocity distribution:

$$\frac{U}{U_*} = \frac{1}{\kappa} \ln \frac{yU_*}{\nu} + A - \frac{\Delta U}{U_*} + \frac{\Pi}{\kappa} 2 \, \mathrm{Sin}^2 \left(\frac{\pi y}{2h} \right) \qquad (1)$$

in which U = flow velocity; U_* = shear velocity; y = distance from the boundary; ν = the kinematic viscosity of the fluid; κ = the von-Karman constant; h = boundary layer thickness or flow depth; A an integration constant and ΔU = the downshift in velocity distribution because of wall roughness. The last term in Eq. 1 is the wake function and Π is the wake parameter. Coleman (1) found that

κ remained the same in flows with clear water and with different concentrations of suspended sediments. However, the value of the wake parameter, Π, increased from 0.19 for clear water to 0.86 for a flow with average sediment concentration of about $5\text{x}10^{-3}$.

From Eq. 1, assuming a linear Reynolds stress distribution, the eddy viscosity, ν_T, is given by

$$\nu_T = \frac{\tau}{dU/dy} = \frac{\kappa U_* y(1-y/h)}{1 + \Pi(\pi y/h)\,\mathrm{Sin}(\pi y/h)} \qquad (2)$$

In the central region of the flow the eddy viscosity distribution is shape like a parabola, with the maximum value located slightly below the mid-depth. This distribution has been verified by Nezu and Rodi (5) using velocity and Reynolds stress measurement.

As an example, consider a clear water flow with a discharge per unit width equal to 500 cm^2/sec in a smooth channel with bed slope $S = 0.0005$. With a wake parameter $\Pi = 0.19$, the uniform flow depth is 9.96 cm and the shear velocity is 2.21 cm/sec. If the same discharge carries sediment so that the value of Π is altered, it has been shown that the flow depth will be reduced, but not by a significant amount (4). For the maximum value of wake paramter of 0.86, which occurred when suspension was near capacity, the new flow depth will be 9.54 cm and the new shear velocity will be 2.16 cm/sec. However, using Eq. 2, it can be shown that the value of eddy viscosity at mid-depth will change from 1.7 cm^2/sec to 0.88 cm^2/sec. Therefore, while the flow depth and shear velocity are changed by only 4.2% and 2.3% respectively, the eddy viscosity at mid-depth has been reduced by 48.2% due to the presence of suspended sediments. As the eddy diffusivity of mass is closely connected with eddy viscosity, one can expected a substantial reduction in eddy diffusivity as well. It follows that the rate of mixing of scalar contaminants will be reduced when the flow is carrying sediment in suspension. This premise can be tested by comparing the spreading of a contaminant in clear water flow and in a flow with sediment suspension.

EXPERIMENT

The experiments were conducted in a 66.7 cm wide flume with a 22 m long test section. The flume slope could be adjusted using screw jacks. A set of louvred gates was used at the downstream end for flow control. A schematic sketch of the experimental setup is shown in Fig. 1.

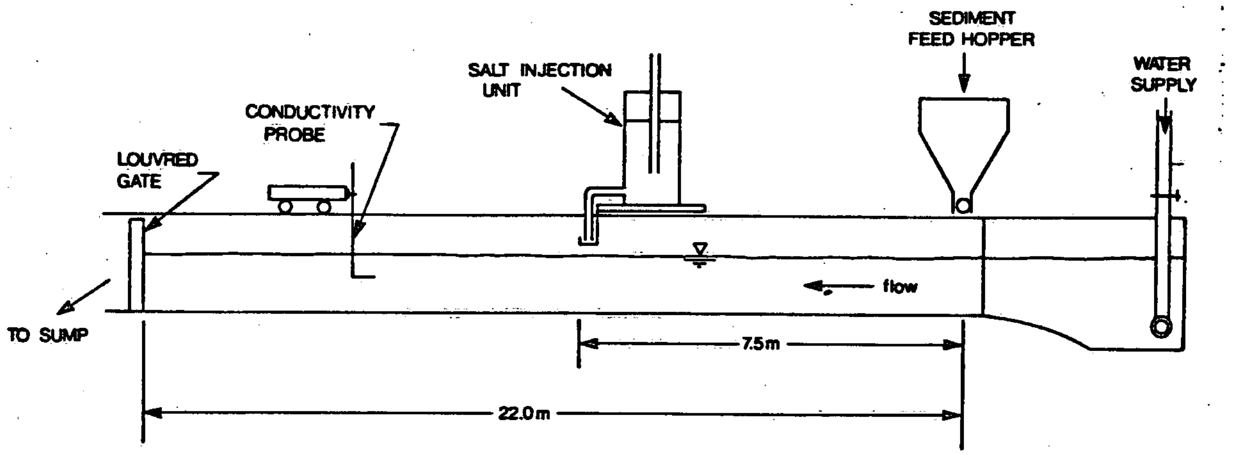

FIG. 1. Schematic sketch of experimental equipment.

Sediment was fed into the flume from a feed hopper located at the beginning of the test section. A rubbber roller, rotating against an aluminium plate, delivered a line of sediments across the whole of the flow width. The feed rate was controlled by adjusting the gap between the roller and the plate. The sediment used was Flex-O-Lite BT12 glass beads with a mean diameter of 0.1 mm and specific gravity of 2.50.

A 10% salt solution, made neutrally buoyant by the addition of methanol, was used as the contaminant. The salt solution was released from a constant head Mariotte tank located 7.5 m downstream from the sediment feed hopper. The salt solution was introduced into a distribution tray which sat across the flume about 0.5 cm above the water surface. Perforations on the bottom of the tray distributed a line source of salt about 1.5 cm wide on to the surface of the flow.

Concentration profiles of salt solution were made at several cross sections downstream of the source along the centerline of the channel, using a conductivity probe in conjunction with an ARISIA data acqusition computer. Each average concentration was evaluated from 100 samples which was obtained at 10 millisecond intervals. Before and after completing each vertical profile, the carriage carrying the probe was moved upstream so that a measurement of the ambient concentration could be made. This information was used to correct for any changes in the background concentration.

The experiment begins with concentration profile measurment in clear water flow. After the profiles for the clear-water flow were completed, the glass beads were fed into the flume. The feed rate was adjusted so that the concentration was close to capacity, i.e., any further increase in feed rate would cause deposition and barchans to form on the flume bottom. The flow was then allowed several minutes to established itself before concentration profiles of the salt were again measured. The sand feed rate was measured periodically by collecting and weighing the discharge from the hopper.

Later, the sand feed rate was reduced and the concentration measurement is repeated for a flow with a substantially lower sediment concentration.

The relevant hydraulic data are summarized as below:

Discharge = 0.1 m^3/sec
Slope = 0.00147
Depth = 15.8 cm
Velocity = 95.1 cm/sec
Shear velocity = 3.9 cm/sec

The average suspended sediment concentrations by volume are 1.9×10^{-3} and 3.8×10^{-4} respectively for the two flows.

RESULTS AND DISCUSSION

Fig. 2 a,b and c shows the typical concentration profiles at x = 1.5 m, 2.5 m and 3.5 m, for clear water flow and for flows with $.38\times10^{-3}$ and 1.9×10^{-3} sediment suspension respectively. Curve fitting of the data is made with a Gaussian profile:

$$c(y,t) = \frac{2^{\frac{1}{2}} q_s}{\pi^{\frac{1}{2}} \sigma} \, \mathrm{Exp} \left(- \frac{y^2}{2\sigma^2} \right) \qquad (3)$$

in which q_s = a source strength.

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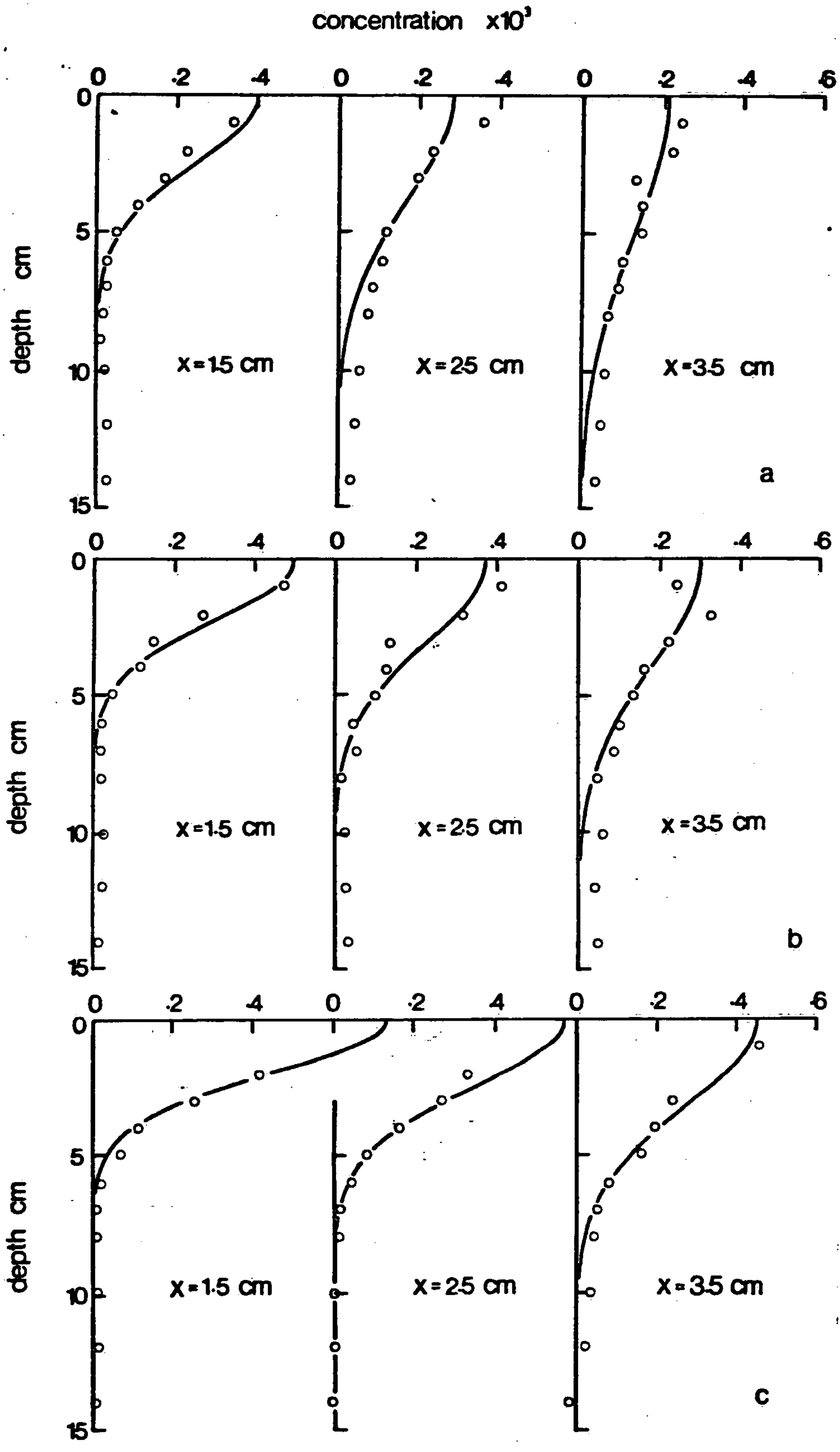

FIG. 2 Concentration profiles for (a) clear water flow, (b) flow with 0.38×10^{-3} by volume of suspended sediments, and (c) flow with 1.9×10^{-3} suspended sediments.

The Gaussian profile, Eq. 3, satisfies the diffusion equation

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial y}\left(E \frac{\partial c}{\partial y} \right) \qquad (4)$$

in which the diffusion coefficient, E, is related to the standard deviation, σ, of the Gaussian profile as follows:

$$E = - \frac{d\sigma^2}{dt} \qquad (5)$$

Table 1 summarize the width (or the standard deviation), σ, and the maximum concentration, c_m, obtained from the curve fitting of the experimental data.

Table 1 σ and c_m of the Concentration Profiles

clear water				$.38\text{x}10^{-3}$ sand				$1.9\text{x}10^{-3}$ sand			
x m	σ cm	c_m ppt	q_s cm.ppt	x m	σ cm	c_m ppt	q_s cm.ppt	x m	σ cm	c_m ppt	q_s cm.ppt
1.5	2.55	.40	1.20	1.5	2.21	.50	1.30	1.5	1.95	.73	1.67
2.0	3.42	.31	1.24					2.0	2.29	.63	1.70
2.5	3.82	.28	1.26	2.5	3.06	.37	1.33	2.5	2.55	.57	1.71
3.0	4.67	.22	1.21					3.0	2.80	.52	1.72
3.5	5.10	.21	1.26	3.5	3.82	.30	1.35	3.5	3.23	.45	1.72

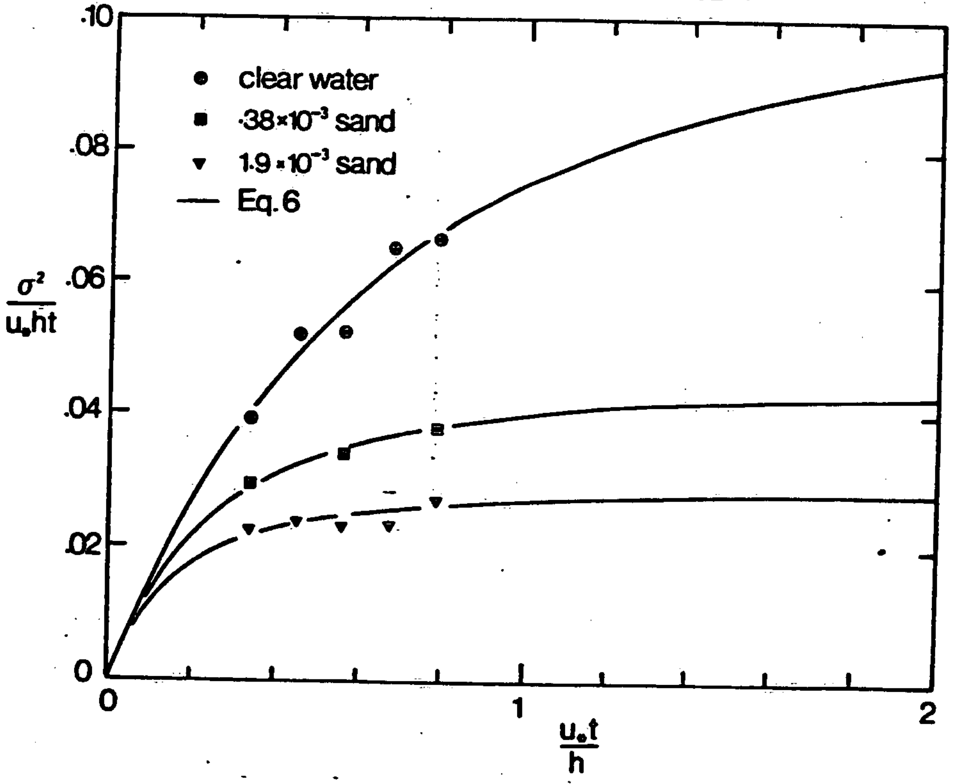

FIG. 3 Change of diffusivity with longitudinal distance from the source.

Fig. 3 plots $\sigma^2/(u_* ht)$ against $u_* t/h$. The time t is related to the distance from the source through the Galilian transformation, i.e. $t=x/U$. If the turbulent diffusion coefficient were a constant, $\sigma^2/(u_* ht)$ would be a constant. However, this is clearly not so for the data of the clear water flow.

When the time is small compared with the integral time scale, T, of the turbulent motion, according to the Taylor's theory of turbulent diffusion (6), the diffusion coefficient increases with the width of the cloud, i.e., $E = u'\sigma$. The diffusion coefficient approachs a constant, E_∞, when time is large in compared with the integral time scale. Kalinske and Pien (3) applied Taylor's theory of difussion to open channel flow and proposed the following expression for σ:

$$\sigma^2 = 2\,u'^2\,T^2\,\{\frac{t}{T} + 1 - \mathrm{Exp}\,(-\frac{t}{T})\} \qquad (6)$$

This expression is in good agreement with the experimental data presented in Fig. 3. The turbulent velocity, u', and the Lagrangian integral time scale, T, obtained from fitting Eq. 6 with the data are given in Table 2. Integral length scale $L = u'T$. The turbulent diffusion coefficient $E_\infty = u'L$. It can be seen from Table 2 that u' remains quite constant while T is reduced significantly for the runs with sediments

Table 2 Length and Velocity Scale of the Turbulent Motion

	T sec	u' cm/sec	L cm	E_∞ cm^2/sec	u'/u_*	$E_\infty/(u_* h)$
clear water	1.43	2.20	3.15	6.68	.564	.106
$.38\times10^{-3}$ sand	.591	2.20	1.30	2.86	.564	.042
1.9×10^{-3} sand	.382	2.18	.832	1.82	.559	.027

CONCLUSIONS: This study has shown that the presence of suspended sediments reduces the spreading rate of a scalar contaminant, which agree with the conclusion drawn from Eq. 1 for the velocity distribution. The decreased spreading rate appears to be caused by a reduction in the integral time and length scales of turbulence while the turbulent velocity was unaffected. This agrees with the suggestion by Yalin (8) that "damping" effect of suspended sediments is a reduction in the scale rather than the intensity of turbulence.

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