

CHAPTER 192

ENTRAINMENT AND TRANSPORT OF FINE SAND BY COMBINED WAVES AND CURRENT: AN EXPERIMENTAL STUDY

by
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Abstract

Experiments have been performed in a large wave flume in order to measure sediment transport rate of fine sand under combined regular waves and current. Instantaneous velocities and concentrations are measured using ultrasonic velocimeters and optical turbidity probes. Suspended transport rates, as obtained from vertical integration of measured fluxes, are decomposed into a mean current and an oscillatory wave components. Under waves only, the wave contribution is in the direction of wave propagation. Under combined waves and current, the wave contribution is found to systematically oppose the direction of superimposed mean current.

1. Introduction

From previous observations, it is well established that sediment transport is enhanced under combined waves and current, due to the stirring action of waves and advection by mean current. However, the relative contribution of both wave and mean motions to suspended sediment transport is a non-linear process which is still poorly understood (e.g Van Rijn, 1991).

Instantaneous values of velocity u and concentration c are classically decomposed into a mean component, time-averaged over the wave period ($\langle x(t) \rangle = X$), and a phase-averaged oscillatory components x_w :

$$\begin{aligned}u(z,t) &= U(z) + uw(z,t) + u'(z,t) \\c(z,t) &= C(z) + cw(z,t) + c'(z,t)\end{aligned}$$

Assuming turbulent fluxes to be small, the time-averaged sediment flux can be written:

$$\langle u(z,t) c(z,t) \rangle = \langle uw(z,t) cw(z,t) \rangle + U(z)C(z) \quad (1)$$

Suspended sediment transport rates, as obtained by depth-integration of equation (1), are then decomposed into a mean current and an oscillatory wave contributions.

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The mean current contribution represents advection of mean concentration by the superimposed mean current or by the second-order eulerian drift induced by the wave motion (Longuet-Higgins, 1953). Under combined waves and current, eddy viscosity models have been used successfully to reproduce mean velocity and mean concentration profiles, assuming enhanced turbulence within the wave boundary layer (e.g. Grant and Madsen (1979)).

The contribution of oscillatory wave motion to suspended transport rates is produced by the asymmetry of the phase-averaged velocity forcing and concentration response. Davies (1990) numerical simulations have shown that the time lag between maximum velocities and bottom concentration peaks is an important parameter which determines the wave contribution effect to suspended sediment transport.

The principal objective of the following series of experiments is to obtain direct estimates of sediment fluxes from instantaneous velocity and concentration measurements under combined waves and current. Part 2 is a description of experimental set-up, measuring apparatus and test conditions. Measurements of mean concentration and mean velocity profiles are presented in Part 3. The effect of wave contributions to suspended transport rates is discussed in Part 4. Results of near bottom phase-averaged concentrations and diffusion of concentration peaks away from the bottom are presented in Part 5. Part 6 is a discussion of results and conclusions.

2. Experimental Set-Up

Experiments were carried out in a large wave flume (1.50m x 1.50m x 79m) which is equipped with a piston type wave maker. The flow is circulated through a pumping system which can generate a current in both directions. The 20 m long test section is made of a 40 cm high surelevated bottom. A 10 cm thick erodible sand bed is placed above the bottom. Two 10 m long sand traps are located on each side of the test section. The measuring section is situated in the middle of the platform as shown on Figure 1.

An optical turbidity probe (OPCON) is used to measure instantaneous concentrations. Instantaneous velocities are measured at the same elevation using 1-D ultrasonic velocimeter. The two probes are located about 15 cm apart in the same cross section and oriented at 45° from the flow direction in order to minimize disturbances of the flow field. Measurements are repeated at different elevations down to a few mm from ripple crests with at least 8 points in the near bottom 10 cm. Measurements are taken at two different lateral positions in the measuring cross section ($y=\pm 25$ cm), in order to check the spatial variability of the signal. Instantaneous velocity and concentration measurements are phase-averaged over at least 50 wave periods in order to estimate both mean and periodic components.

Bed elevations are recorded every 4.5 mm using an electromagnetic bed profiler along three longitudinal sections ($y=0, \pm 25$ cm) above both platform and sand traps. Measurements are made before and after each test, in order to estimate total sand volume per channel width ($L \Delta z_b$) passing through the measuring section. Total transport rates in dry weight, Q_t , is given by:

$$Q_t = \frac{L \Delta z_b (1-n) \rho_s}{\Delta t} \quad (2)$$

where n is the sediment bed porosity ($n=0.4$), ρ_s , the sediment density ($\rho_s = 2.65 \text{ g/cm}^3$) and Δt , the duration of experiment. Mean bed level measurements z_b need to be corrected for small variations in the reference elevation in order to satisfy mass conservation. Test duration Δt must be less than one hour in order to minimize bed level variation during experiment due to erosion or deposition processes.

The sand bed is made of a well sorted fine sand with mean diameter $d_{50}=0.09 \text{ mm}$ and mean settling velocity $w_s = 0.7 \text{ cm/s}$. The water depth h above the platform is 60 cm . A series of 10 tests have been carried out for wave periods T of 1.5, 2 and 2.5s and an incident wave height H_i of about 25 cm. Longitudinal reflected waves, H_r , are generally less than 10% of incident waves. For each wave condition, a mean current U_r of about 20 cm/s at a reference level $z_r=35 \text{ cm}$ is superimposed to the wave field in or against the direction of wave propagation. Hydrodynamic conditions are summarized in Table 1 in which a positive sign means a following current.

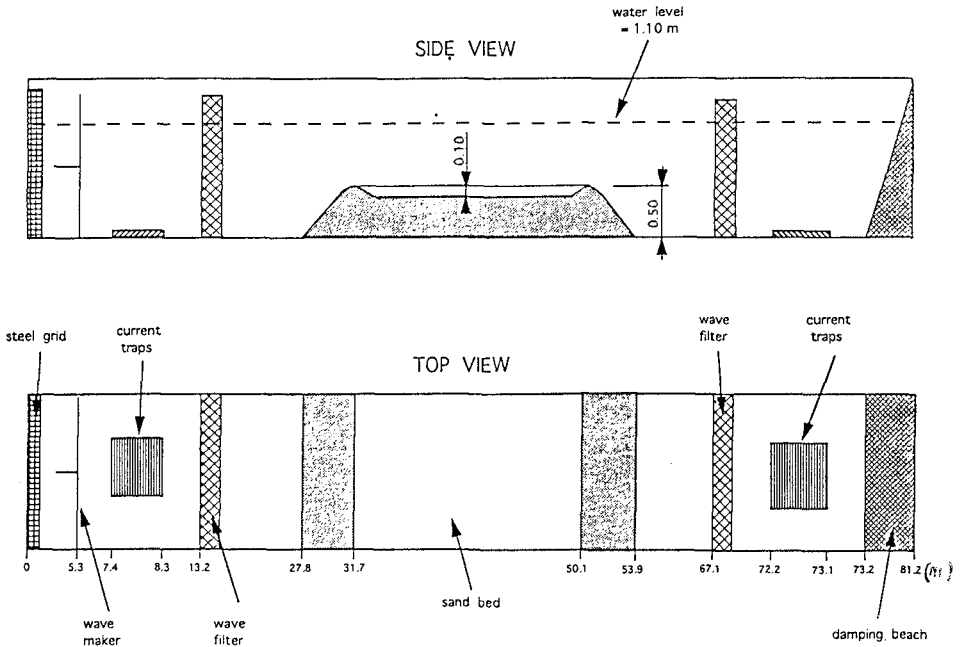


Figure 1: Side and top views of the wave flume

3. Experimental Results :

Bedforms:

Bedforms are two-dimensional for $T=1.5$ s and become irregular three-dimensional for $T=2.5$ s. Bedform dimensions are obtained from statistical analysis of bed profiler data. Typical bedforms heights do not show significant variation with flow parameter ($\delta_r = 0.65$ cm), while wave length λ_r slightly increases with wave period from 5 to 7 cm. (see Table 1).

Test N°	T (s)	Hi (cm)	Hr (cm)	Ur (cm/s)	λ_r (cm)	δ_r (cm)
35	1.5	23.2	1.0	- 4.6	4.8	0.7
39	2	23.2	1.3	- 5.75	5.5	0.7
42	2.5	25.0	2.15	- 5.9	6.7	0.6
36	1.5	18.8	1.05	17.4	5.0	0.6
40	2	21.0	2.1	17.4	5.0	.65
77	2.5	17.8	2.6	17.0	5.6	.7
38	1.5	17.5	1.25	- 17.0	4.8	0.6
41	2	21.1	1.6	- 18.7	5.5	0.7
54	—	20.1	2.20	-32.75	—	—
45	2.5	21.0	1.6	-17.6	5.8	.6

Table 1: Hydrodynamic test conditions

Mean velocity profiles:

In the case of waves only, there is a small eulerian drift which is in the direction of wave propagation near the bottom and against it in the outer flow ($U_r=-4$ to -5 cm/s) as shown on Figure 2.

Under combined waves and current, mean velocity profiles are fitted to a logarithmic profile in order to estimate both mean friction velocity u^* and apparent roughness height k_a , assuming a Karman constant $K=0.4$ (see Table 2):

$$U = \frac{u^*}{K} \log \left(\frac{33z}{k_a} \right) \quad (3)$$

The main effect of the waves on the mean velocity profiles is to increase the equivalent roughness height k_a as compared to physical roughness ($k_s=1.5 \delta_r$). This effect is larger for opposing waves and current than for following waves and current. These results are qualitatively in good agreement with expectations from theoretical models (e.g. Grant and Madsen (1979)) and previous observations (e.g. Nap and Van Kampen (1988)).

Mean concentration profiles:

In all our experiments, sediments stay within a thin (<5cm) near bottom layer. An exponential concentration profile gives a reasonably good fit to measurements as indicated by regression coefficients $r > 0.95$. Results are interpreted in terms of bottom concentration C_0 and suspended layer thickness L_s , according to Nielsen's (1979) model (see Table 2):

$$C = C_0 \exp\left(-\frac{z}{L_s}\right) \quad (4)$$

In the case of three dimensional bedforms ($T=2.5s$), there is a lot of scatter in measurements as shown on Figure 3. Under waves only, decrease of mean bottom concentrations with wave period may be due to changes in bedforms geometry from 2D to 3D as period increases.

Under waves only, the suspended layer thickness approximately scales with bedforms height ($L_s = 2$ to $3 \delta_r$). Significant increase of suspended layer thickness is observed for a following current which is in good agreement with expectations from previous models and observations. In the case of opposing current, this effect can only be observed by increasing opposing current intensity (Test 54). In the other tests with opposing current, the suspended layer thickness is approximately the same as for waves alone. For longer waves with opposing currents ($T=2.5s$), L_s is actually smaller than for waves alone.

Test N°	u^* (cm/s)	k_s (cm)	r	L_s (cm)	C_0 (g/l)	r
35				1.13	35.0	-0.99
39				0.99	30.9	-0.99
42				1.60	15.7	-0.96
36	1.90	8.1	0.95	1.77	9.8	-0.95
40	2.20	12.7	0.98	1.26	16.7	-0.98
77	2.37	14.2	0.95	2.18	8.2	-0.97
38	-1.19	14.1	-0.95	1.05	12.6	-0.95
41	-1.43	15.0	-0.94	1.07	22.6	-0.98
54	-1.96	8.9	0.92	1.90	9.5	-0.99
45	-1.47	14.7	-0.98	0.98	27.8	-0.96

Table 2: Test results

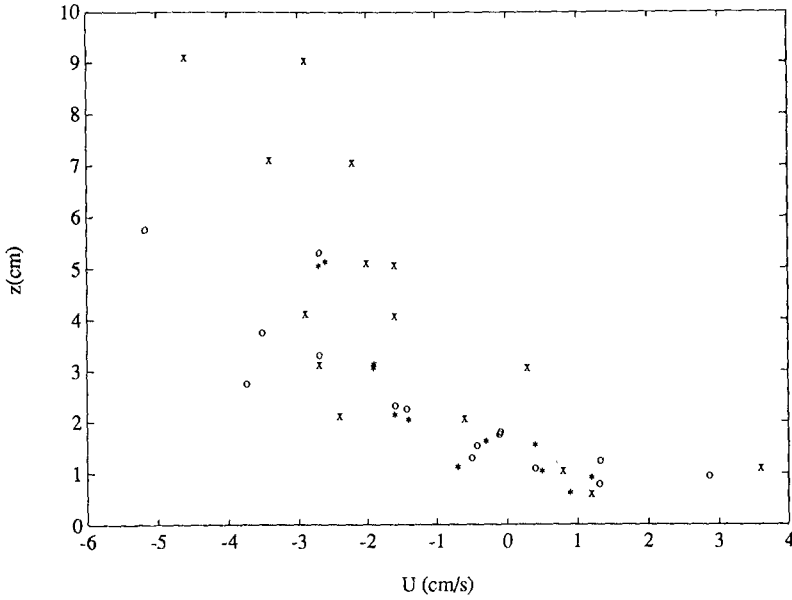


Figure 2: Mean velocity profiles under waves only
Tests 35 (o: T=1.5 s), 39 (*: T=2s), 42 (x: T=2.5s).

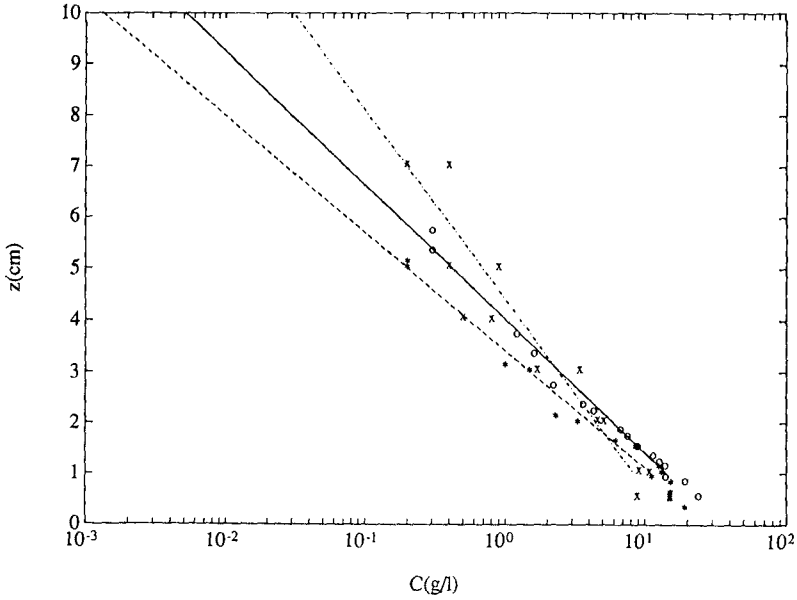


Figure 3: Mean concentration profiles under waves only
Tests 35 o: T=1.5 s), 39 (*: T=2s), 42 (x: T=2.5s).

4. Transport rates

Suspended transport rate estimates are decomposed into a wave and a mean current contributions according to equation (1). Measurements are averaged between the two-measuring points at ($y=\pm 25\text{cm}$) across measuring section. Total transport rates Q_t are estimated from bed profiler data according to equation (2). In most cases, the difference between total transport rates Q_t and suspended transport rates Q_s is less than the spatial variability of measurements (30%). This indicates that bed load transport remains relatively small. In the case of opposing currents, net suspended transport rates are also small so that bed load contributions are not negligible anymore; total transport rates are then significantly enhanced in the direction of opposing mean current due to the small bed load contributions (see Table 3).

Under waves only, total transport is in the direction of wave propagation and increases with the wave period. Contribution of the weak eulerian drift to total transport Q_c remains small. Under combined waves and current, the wave contribution Q_w to total transport systematically opposes the mean current direction. The direction of total transport depends then on the relative intensity of both contributions. In the case of following current, the wave contribution is opposed to the direction of wave propagation but remains small compared to the mean current contribution Q_c , so that net transport is in the direction of wave propagation.

Test N°	Q_c $\times 10^{-4}$	Q_w $\times 10^{-4}$	Q_s $\times 10^{-4}$	Q_t $\times 10^{-4}$
35	21	100	121	81
39	2	112	114	137
42	10	160	170	167
36	142	-22	120	126
40	135	-55	80	106
77	166	-38	127	93
38	-29	36	8	-19.5
41	-63	147	84	20
54	-143	133	-10	
45	-60	95	36	-14

Table 3: Sediment transport rates (Units are in kg/m/s)

5. Instantaneous concentrations

Bottom concentration:

Under waves only, the bottom phase-averaged concentration is mainly periodic at half the wave period ($T=2s$) and concentration peaks occur near current reversal ($u(t)=0$), as shown on Figure 4.a. Under combined waves and current, only one maximum concentration peak is observed which systematically occurs slightly after flow reversal when the instantaneous current is opposed to the mean current direction as shown on Figures 4.b and 4.c for $T=2s$. Near the bottom, the contribution of the wave motion to total transport is then expected to oppose to the mean flow direction.

Diffusion of concentration peaks:

Diffusion of concentration at various elevations is shown on Figure 4.a under waves only. The first peak occurring near flow reversal when current starts to oppose direction of wave propagation, cannot be observed away from the bottom. Phase-averaged concentrations show only one maximum peak occurring when current is in the direction of wave propagation ($u(t)>0$). Flux due to oscillatory motion is then expected to be positive at all elevations.

Diffusion of maximum concentration peaks away from the bottom can be observed on Figure 4.b for following current and on Figure 4.c for opposing current. Concentrations are maximum when instantaneous current is negative ($u(t)<0$) in the case of following current and positive ($u(t)>0$) for opposing current. Flux due to oscillatory motion is then expected to oppose the mean current direction at all elevations.

Flux profiles:

Typical flux profiles, time-averaged over the wave period, obtained for waves only, and combined waves and current are shown on Figures 5.a, b, c ($T=2s$). As expected from near bottom concentration response and diffusion of concentration peaks, sediment transport flux due to oscillatory wave motion is in the direction of wave motion in both cases of waves only and opposing current and waves and in the opposite direction for following current.

6. Discussion of results and conclusions:

Results obtained for the mean current and wave contributions to total sediment transport make a qualitatively consistent picture. Under combined waves and current, the wave contribution is found to systematically oppose the mean current direction. In this case, the direction of the wave contribution to total sand transport can be explained by the asymmetrical bottom concentration response. Only one maximum concentration peak is observed which occurs slightly after flow reversal when the instantaneous current starts to oppose the mean flow direction.

It is interesting to note that these results are qualitatively similar with observations by P. Murray and al (1991) in the sheet flow regime. They also found that the total sediment transport rate under combined waves and current is systematically reduced by its wave component; their observations confirm the existence of one maximum peak in the bottom concentration which occurs when the

instantaneous current is opposed to the mean flow direction. These observations suggest that the reduction of total transport by the wave contribution is a fairly general result occurring in both ripples and sheet flow regimes.

Under waves only, the effect of the eulerian drift under waves only as well as second-order Stokes component on mean phase-averaged concentrations still needs to be clarified. A similar dissymetry on the phase-averaged concentration response can be observed under waves only as under opposing current and waves so that transport due to wave motion is in the direction of wave propagation in both cases.

The effect of bedforms dimensions and of measuring technique on concentration profiles is also unclear. In the case of three dimensional bedforms ($T=2.5s$), a spatial averaging technique may become necessary, considering spatial variability of signal.

Acknowledgments

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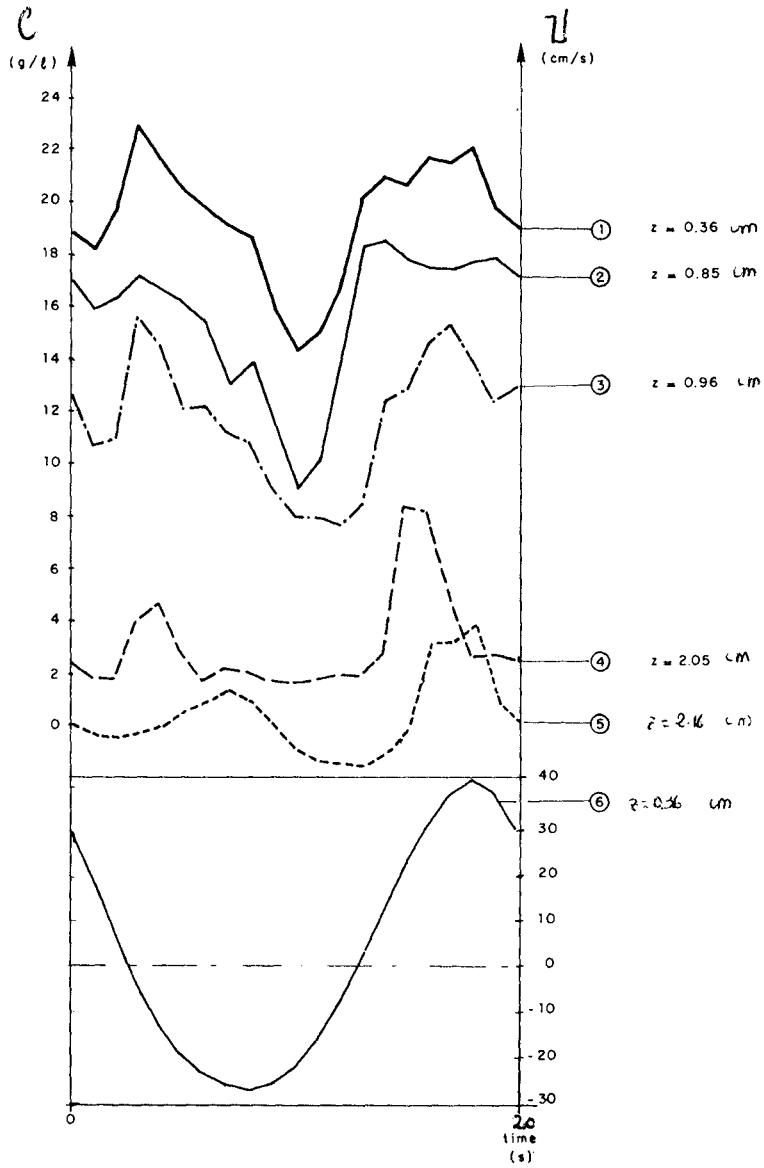


Figure 4.a: Phase-averaged concentrations (1-5) and bottom velocity (6) under wave only for $T=2$ s (Test 39)

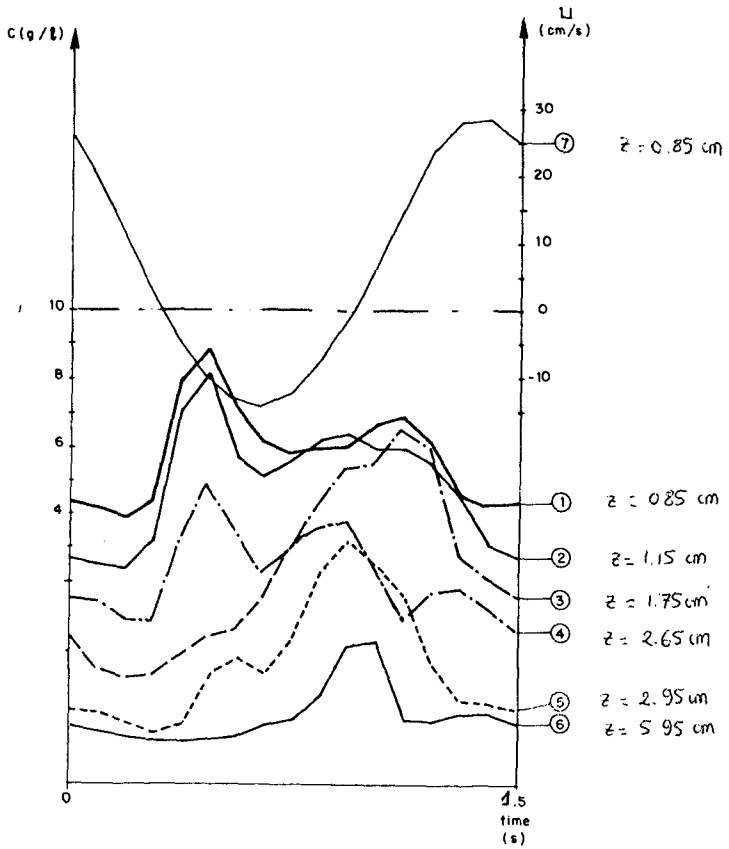


Figure 4.b: Phase-averaged concentration (1-6) and bottom velocity (7) under wave and following current for $T=1.5$ s (Test 36)

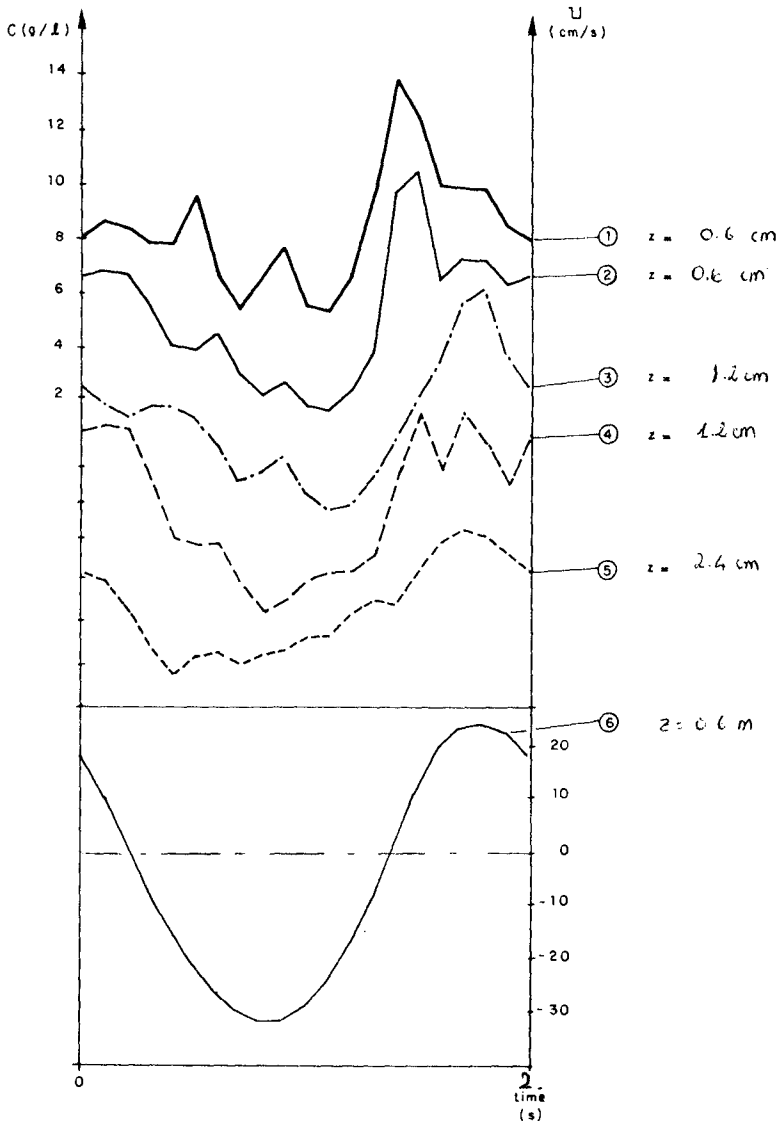


Figure 4.c: Phase-averaged bottom velocity (6) and concentration at various elevations (1 to 5) under wave and opposing current for $T=2$ s (Test 54)

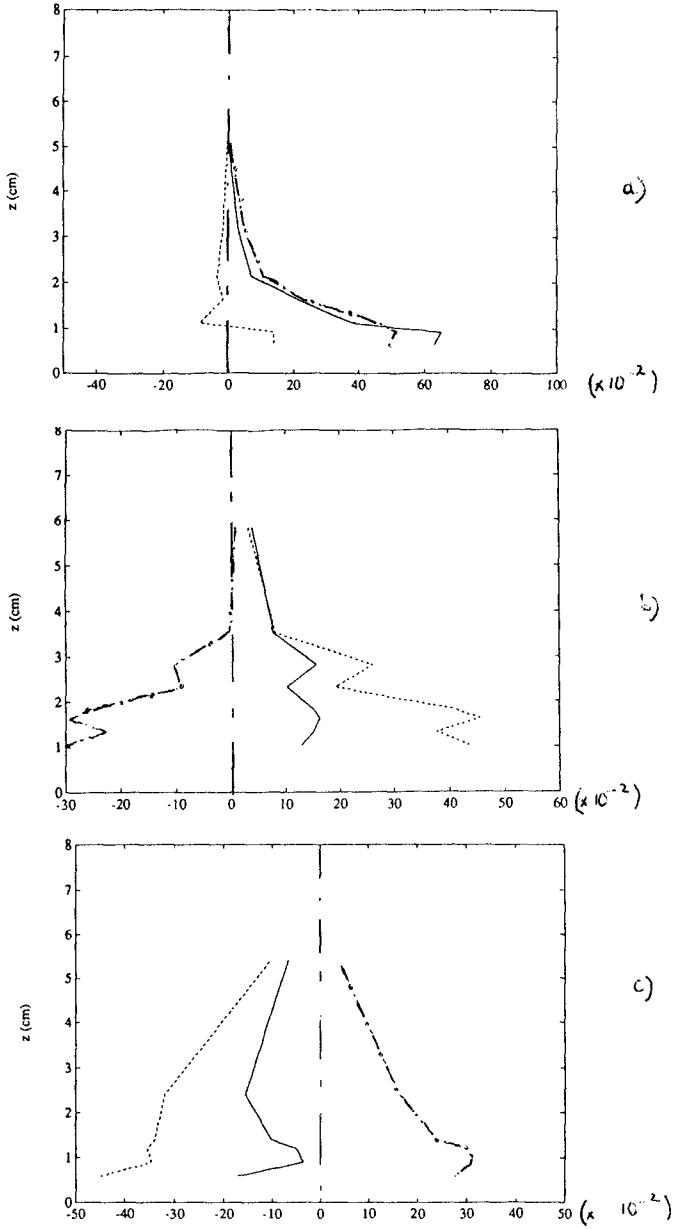


Figure 5: Time-averaged sediment flux profiles at $T=2s$ ($\langle u(t) c(t) \rangle$): —; UC: - - -; $u_W(t)c_W(t)$: - · - ·. Units are in $Kg/s/m^2$.
 a) Wave only (Test 39); b) following current (Test 40); c) opposing current (Test 54).