CHAPTER 75

Developing Wave-Current Boundary Layers

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Abstract

When applied to real engineering problems, mathematical models of combined wave-current flows usually assume that both wave and current properties remain in a quasi-steady state. Shear stresses and other flow parameters are calculated for instantaneous values of wave height and current strength, regardless of the changes being induced by tides, winds, or wave grouping.

This paper describes tests carried out in a wave flume to investigate velocity profiles, bottom shear stresses and water surface characteristics under gradually developing flow conditions, such as those created when a group of waves is superimposed onto a pre-existing current or when a steady current is added to a train of regular waves. Results indicate that, at laboratory scale, the water surface characteristics adapt within a few wave periods to changes in superimposed waves or current, but that mean velocity profiles and shear stresses may take considerably longer to respond to the new flow conditions.

Introduction

In the assessment of sediment transport at the seabed or in the design of structures to stand in coastal waters, a large number of mathematical models

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are now available to describe the local wave and current processes. Approximately thirty of these models include the effects of wave-current interactions, and their calibration has generally been based on the assumption of a quasi-steady relationship between the wave properties and the current strength [Simons et al. (1988)]. In practice, with coastal hydrodynamics dominated by cyclic tidal currents and storm-generated currents and waves, this is not the case, although it remains to be shown whether the quasi-steady approach gives an adequate prediction. Some models [Christoffersen and Jonsson (1985); Davies, Soulsby and King (1988)] have included the effects of unsteady currents, but these are the exceptions. The DSK (1988) model predicts a rapid change in boundary layer characteristics if the net flow rate, rather than the driving pressure gradient, is maintained after the addition of the waves. However, if instead, the pressure gradient is held constant, then the change to stable wave-current conditions is far less rapid.

The present paper describes a laboratory study aimed at measuring the characteristics of developing flows, in particular looking at the rate at which bottom shear stresses and water surface properties in wave-current flows adapt to varied currents and isolated wave groups.

Wave-Current Interaction

Before going on to consider cases where current strengths are being varied or where short groups of waves are being superimposed on a current, it is worth noting the results from previous studies carried out under "steady" combined wave-current conditions, when regular waves of constant height propagate onto a steady unidirectional current.

Results from earlier experiments in flumes and in the field indicate that the properties of both waves and currents are changed from their separate values. These observations have been used to calibrate and to confirm the physical assumptions necessary in the derivation of wave-current mathematical models. For instance, the addition of wave-induced oscillatory motion has been shown to be capable of inducing orders-of-magnitude increases in the apparent bed roughness and the bottom shear stress felt by the mean current, although the mean velocity profile retains a logarithmic region [Bakker & Doorn (1978); Brevik & Aas (1980); Kemp & Simons (1982), (1983); Tanaka, Chian & Shuto (1983)]. Turbulence intensities determined from the fluctuations about the ensemble averaged velocities are increased within the oscillatory boundary layer; Simons et al. (1988) found that the increase in u' is of the same order as the increase in u_* defined from the mean velocity profiles.

As a result of the extra frictional resistance at the bed, it has been demonstrated in flume tests that the mean water level slope increases if a constant volume flow rate is to be maintained. Also, rates of wave energy dissipation change in the presence of co-existing currents. Simons, Grass & Kyriacou (1988) showed that attenuation rates decrease if waves propagate over a following current, but that they can increase if the current flows against the direction of wave propagation. It was suggested that this phenomenon could be explained in terms of a wave friction factor, using the definition proposed by Jonsson (1966).

Experiments

The present test programme was performed in a recirculating laboratory flume 610 mm wide and 30 m long, with a still water depth of 300 mm and a horizontal bed roughened with 10 mm limestone chippings. A two channel laser Doppler anemometer was used to determine instantaneous Reynolds stresses and simultaneous horizontal and vertical velocities. The experimental set-up was similar to that described by Simons et al. (1988).

During the test programme, 10 different developing flow cases were investigated, where waves were gradually superimposed onto an existing steady current or vice versa. Seven tests involved running a steady current for one minute, adding waves for 6 minutes, then returning to the current-only state for a further minute. In the other three tests, waves were first propagated through still water for a minute, a current introduced gradually over an 80 second period and run for a further 5 minutes, then the waves turned off and a steady current left to flow for another minute. The experimental conditions are set out in **Table 1.**

Each test was repeated 10 times, with the 2-channel

Run	Initial State:			Superimposed flow:			Final state:		
	u	T	H	u	T	H	u	T	H
	mm/s	s	mm	mm/s	s	mm	mm/s	s	mm
WK4.D	75	-	-	75	0.7	22.6	75	-	-
M4.D	190	-	-	190	0.7	18.2	190	-	-
ST4.D	250	-	-	250	0.7	16.2	250	-	-
ST4.I	250	-	-	250	1	36.9	250	-	-
ST3.I	250	-	-	250	1	27.7	250	-	-
M4.I	190	-	-	190	1	40.7	190	-	-
WK4.I	75	-	-	75	1	50.5	75	-	-
US4.I	-	1	50.7	250	1	27.7	250	-	-
UM4.I	-	1	50.7	190	1	40.7	190	-	-
UW4.I	-	1	50.7	75	1	50.5	75	-	-

Table 1. Parameters for the developing flow tests.

laser anemometer set at different heights above the bed. Water surface (wave height and MWL) was also recorded simultaneously at 10 points along the flume in 3 groups such as to make it possible to identify and compensate for reflected waves moving back up the flume from the beach. Water surface data were recorded on computer disc every 140ms through a high speed analogue to digital converter, while velocities were stored on magnetic tape for subsequent processing.

In order to analyse the results from these varied flow tests, it was necessary to develop a series of computer programmes capable of synchronizing a large number of independent data files. Each of these files contained a time series of velocities or Reynolds stresses at the chosen measuring positions through the boundary layer, from which full depth profiles of mean velocity, turbulence and Reynolds stress could be generated at different stages through the tests (using appropriate short-term averaging). Simple ensemble-averaging was not possible because of the imposed variation in the "mean" velocities. Time series of MWL and wave height at 3 widely spaced locations along the flume were also required, from which it was possible to derive information on wave attenuation and mean water surface slope. This process was complicated by having only 10 simultaneous sets of water surface data, closely spaced in three groups (5m, 15m, and 25m from the wave paddle) from which to interpret the significance of reflected waves in the flume.

Two wave periods [0.7s, 1.0s.] and two wave heights [25mm, 40mm.] were considered in combination with three co-directional currents [75mm/s, 190mm/s, 250mm/s].

Results

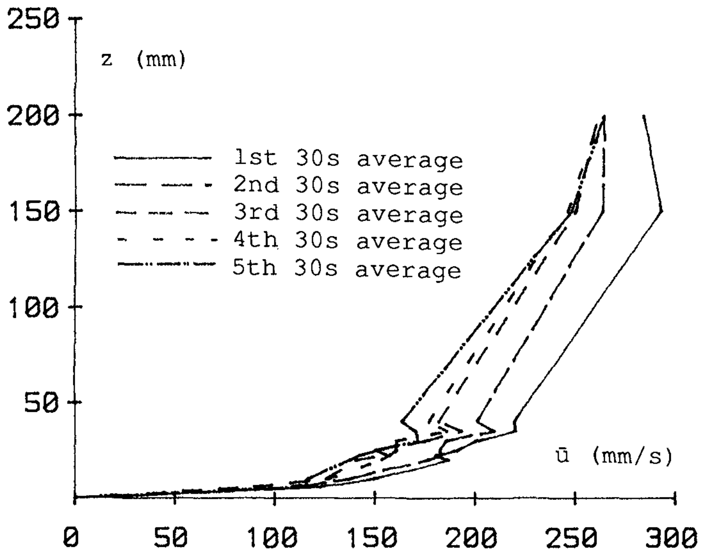

Fig.1 Boundary layer profiles of horizontal velocity at 30s intervals after the superposition of waves [T=1s;].

In the tests where waves were superimposed onto a pre-existing steady current, it was found that the mean velocity profile took approximately 200 wave periods to stabilize under the new combined flow conditions. The increase in shear stress at the boundaries slowed the mean current, causing a redistribution of flow across the channel. Fig.1 shows mean velocity profiles at 30 second intervals after generation of the first wave at the paddle 15 m upstream. Despite the scatter caused by such a short averaging period, the mean velocities can be seen to be more or less established in a stable profile after 150s; over the next 50s, velocities increase towards their initial current-only values near mid-depth, but with slower flow maintained near the bed and at the surface. It should be remembered here that the mean velocities reflect not just the superimposed current flow but also wave-induced mass transport.

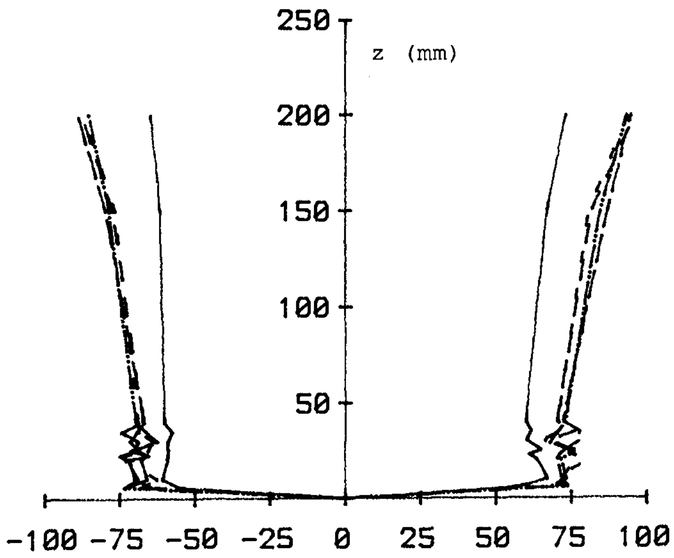

Fig.2 Development of Horizontal Oscillatory Velocities at 30s intervals after the start of wave generation.

In order to determine orbital velocity amplitudes and turbulence intensities during the transitional period after the addition of the waves, a second order curve fit was applied to the unprocessed velocity data to establish the oscillatory component. The short term mean velocity and the reconstituted 2nd order orbital velocity were then subtracted from the raw data, leaving the turbulent velocity fluctuations. The root-mean-square of these short samples (5 s; 30 s) were then used to quantify the instantaneous turbulence intensities.

The same procedure was applied to horizontal and vertical velocity components and to Reynolds stresses. Fig.2 shows the variation in horizontal orbital amplitude through the depth at time intervals corresponding to those in fig.1; the wave motion was found to be stable after the generation of 20 or so waves.

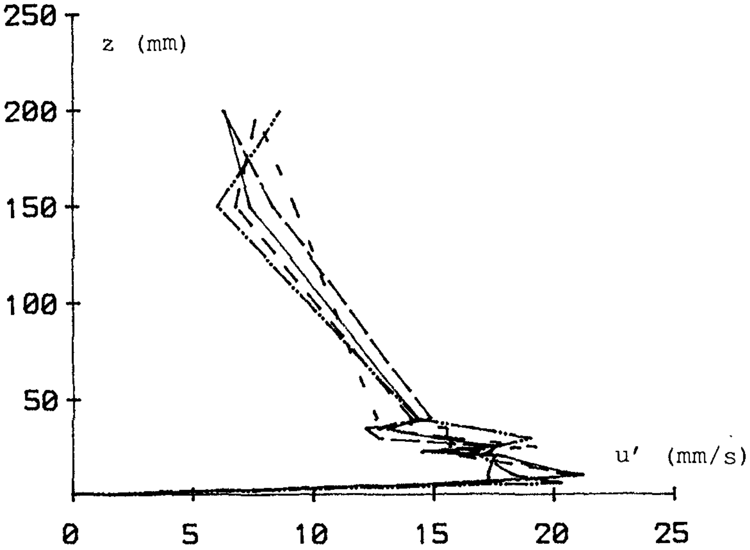

Fig.3 Development of Horizontal Turbulence Intensities at 30s intervals after waves are superimposed.

Profiles of turbulence intensity through depth showed considerable scatter, as the 30s averages plotted in fig.3 demonstrate. The profile containing the highest values near the bed relates to data sampled early in the test, and is probably attributable more to the change in mean velocity during the initial 30s sample rather than to real turbulence. Careful study of the profiles of u′ and v′ could justify a conclusion that stable wave-current conditions have been established after 30 or so wave periods, but such a view must be taken as tentative.

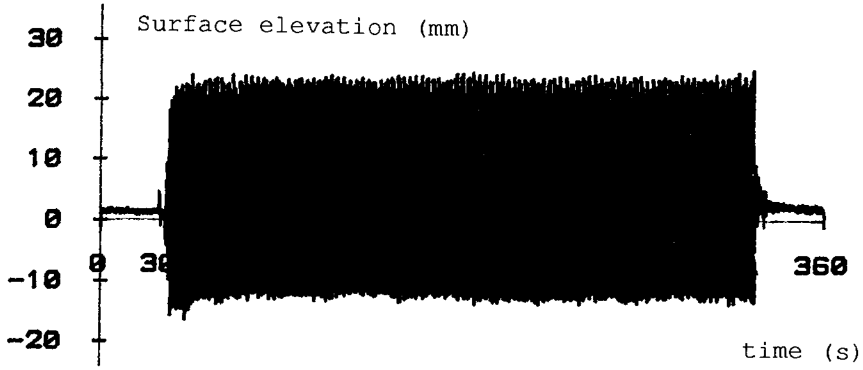

Fig.4 Variation in water surface elevation when waves are added to a steady current: a) 5m from the wave paddle; b) 25m from the wave paddle.

Turning now to the behaviour of the water surface, fig.4 records the water surface movement at the measuring station closest to the wave paddle (top) and near the beach, 20m. downstream (bottom). Using the second order curve-fitting routine, it was possible to analyse these data further to yield time series of wave heights (fig.5) and "mean" water levels (fig.6) for the corresponding tests. These results confirm earlier observations that the mean water level slope is increased by the addition of waves. Figs.4 and 6 both show the water level rising at the paddle end of the flume by between one and two millimetres, with a corresponding fall at the beach end. This change takes approximately 30s. to stabilize, whereas wave heights build up to a constant value within three or four seconds of the arrival of the first wave. The regular oscillation apparent in the MWL traces is due to the use

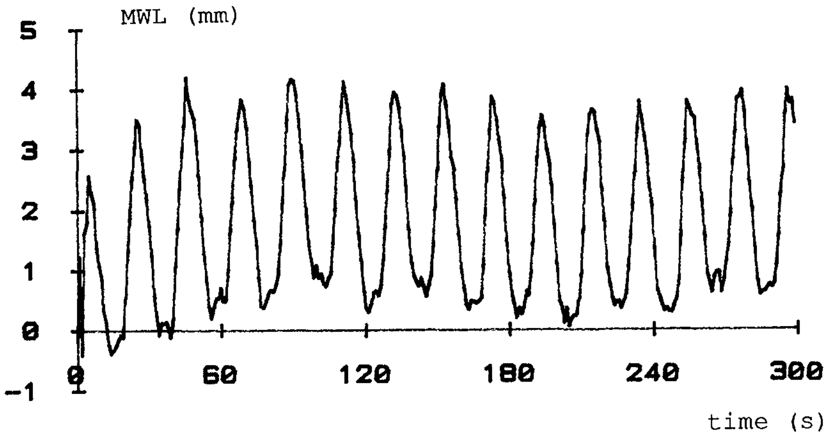

Fig.6 Time series of mean water level 5m from the paddle when waves are added to a steady current.

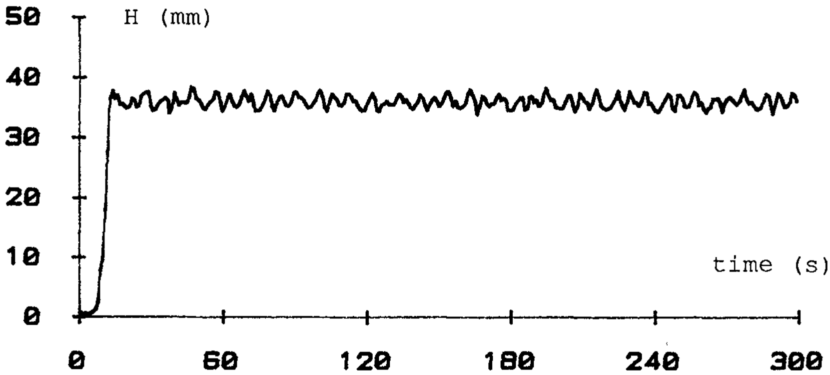

Fig.5 Time series of wave heights 5m from the paddle when waves are added to a steady current.

of a digitizing interval which does not exactly repeat at the same phase each wave cycle.

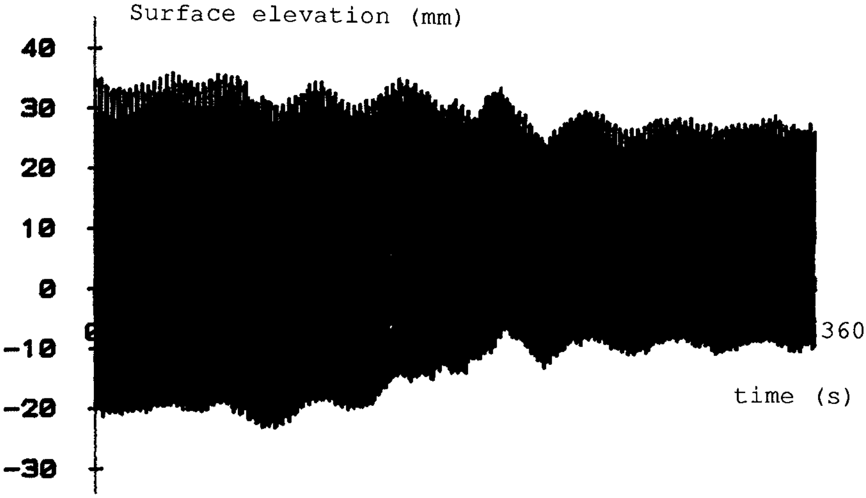

Fig.7 Time series of wave heights 5m from the paddle when waves are added to a steady current.

All the results described above relate to the first series of tests where waves are added to a pre-existing current. Analysis is still to be completed for the tests where a current was gradually imposed onto regular waves. However, fig.7 shows the water surface movement at the 5m position along the flume during one of these runs. Despite the great care exercised in opening the current control-valve, a seiche wave has clearly been set up in the flume. This emphasizes the difficulty in carrying out and analysing data from these unsteady tests.

Conclusions

From the profiles of mean velocity and turbulence characteristics, it has been shown that stable wave-current conditions may not be established until nearly

200 waves have passed the LDA measuring position. However, a far more rapid time-scale (say 15 wave periods) was evident in the changes in hydraulic gradient along the flume induced by the addition of waves to a current.

These results suggest that care needs to be taken when using wave-current models in coastal engineering for the prediction of mean velocities and consequential sediment transport rates if wave conditions are changing rapidly. However, a quasi-steady approach appears appropriate where changes in wave characteristics and mean water levels are the only consideration.

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