CHAPTER 269

KINEMATICS AND SHEAR STRESSES FROM COMBINED WAVES AND LONGSHORE CURRENTS IN THE UK COASTAL RESEARCH FACILITY

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Abstract

The paper describes a series of experiments involving regular and random waves propagating over an orthogonal longshore current in the UK Coastal Research Facility at Wallingford. Mean and wave-induced velocities have been measured above a horizontal fixed rough bed using three acoustic velocimeters, and simultaneous measurements of mean and oscillatory bottom shear stress have been made with a UCL shear cell. Wave-induced shear stresses have been expressed as friction factors and compared with widely used empirical formulae. Other results have been compared with predictions for shear stress and apparent bed roughness from eight wave-current theories. The predicted enhancement of these parameters is judged against the relative strengths of the waves and currents tested, and against the practical range of conditions achievable in such laboratory basins.

Introduction

In trying to understand the effects of waves and currents on the coastal environment it is important to be able to predict the forces exerted on the seabed by the fluid motion and, conversely, what effect the seabed has on that motion. Such boundary layer processes are included in the wave-current interaction elements of the new generation of coastal numerical models, but there remains insufficient reliable data against which predictions from these models can be validated. Researchers at UCL are involved in a number of projects aimed at filling this gap.

In an earlier series of tests performed by the UCL group [Simons *et al.* (1992), (1994)], bottom shear stresses were measured directly using a novel shear cell device under conditions including regular and random waves propagating across an orthogonal current. This work suggested that waves have a significant effect on the current-induced mean shear stresses but that an additional current makes little difference to the wave-induced stresses. However, the relatively small basin used for those tests meant that the flows were not all fully rough turbulent. To produce

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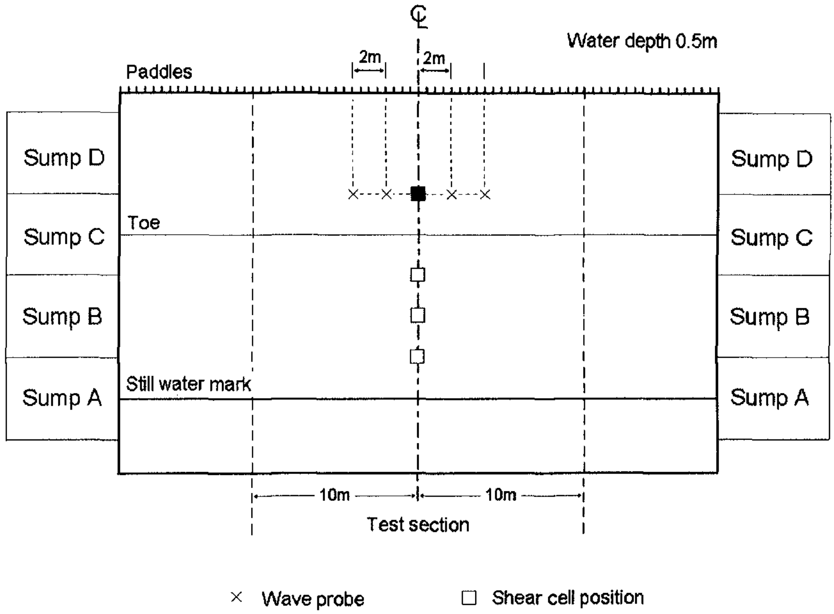

Figure 1 Schematic layout of UK Coastal Research Facility

results which can be applied to field-scale conditions and provide a valid test for the models, the experiments reported here have been carried out in the UK Coastal Research Facility (UKCRF) at Reynolds numbers well beyond transition and over a large fixed bed roughness.

The number of models in the literature which offer possible solutions to the problem of wave-current interaction in a turbulent coastal flow field is too extensive for detailed consideration here. All such models require empirical assumptions about the physical structure of the combined flow, and many also lead to difficult calculations in achieving a solution. In their review of the subject, Soulsby *et al.* (1993) put forward a simplified method for applying these theories using a set of standard formulae to relate the significant parameters. Each model is characterised by a unique set of 26 coefficients - found by fitting curves through model solutions for a wide range of input parameters - and these are used in the standard formulae to determine mean and maximum shear stresses. These "parameterised" versions of certain models are compared with the present experimental data later in this paper, both in terms of the enhanced bottom shear stress and also the apparent increase in bed roughness when waves are superimposed.

UK Coastal Research Facility

The UKCRF has been designed to provide a controlled environment in which various coastal processes can be simulated at relatively large scale. It measures 54m by 27m overall, with a central test region 20m by 15m (**fig.1**), and is designed for water depths between 0.3m and 0.8m - although the present tests have been performed with 0.5m depth. The wave generation system consists of 72 individually controlled wave boards (each 0.5m wide) mounted along one wall of the basin. This can produce orthogonal or oblique-incidence regular or random waves up to 30^0 from shore-normal, with periods between 0.8s and 3.5s and heights up to 0.25 metres.

Currents are circulated by 4 independent reversible flow pumps and are introduced into the basin through 40 inlet flumes, each controlled by its own undershoot weir, with a matching set of flumes at the outlet end. One of the novelties of the UKCRF is that this system allows wave-driven currents to be circulated and at the same time allows for simulated wind- or tidally-driven longshore currents to be superimposed. Another is that the pumps act under programmable control, thus allowing time-varying (tidal) longshore currents with a user-defined period to be superimposed onto a controlled sequence of waves.

The facility is equipped with a wide range of instrumentation. For the present tests, a UCL shear cell was used to make direct measurements of the wave- and current-induced bottom shear stresses on the horizontal region of the basin. Briefly, the shear cell consists of a thin 250mm diameter plate supported level with the bed on four thin needles and deflecting laterally under the action of any horizontally applied shear stress at the bed. The movement (less than 0.5 mm) is recorded by two orthogonal eddy-current sensors and converted into an analogue voltage - as described in Grass *et al.* (1995).

A 3-d fibre-optic laser Doppler velocimeter (restricted here to 2-d operation only) provided detailed information within the bottom boundary layer; three Sontek 3-d acoustic Doppler velocimeters (ADV) were mounted, one above the other **(fig.2)**, on the z-axis of the instrument deployment bridge, thereby speeding up the process of measuring full vertical profiles of mean and wave-induced velocities; and 4 wave probes were deployed close to the shear cell to provide measurements of wave height and period.

To control the ADV's when they are operating near the centre of the basin, it is necessary to deploy a dedicated computer on the instrument carriage. The system is then operated from the control room via long cables linking the keyboard, screen and data logger to the remote processor.

For the present set of tests, the bed was roughened with nominal 10mm diameter granite chippings stuck to the concrete base of the basin and also to the surface of the UCL shear cell **(fig.3)**. The bottom roughness was stuck as a single layer, with a thin coating of adhesive painted onto the bed, the chippings rolled into it and left to set, and the surplus swept off some time later. The observed Nikuradse roughness was 18.7 mm.

Long-crested waves were generated in the offshore region and propagated across

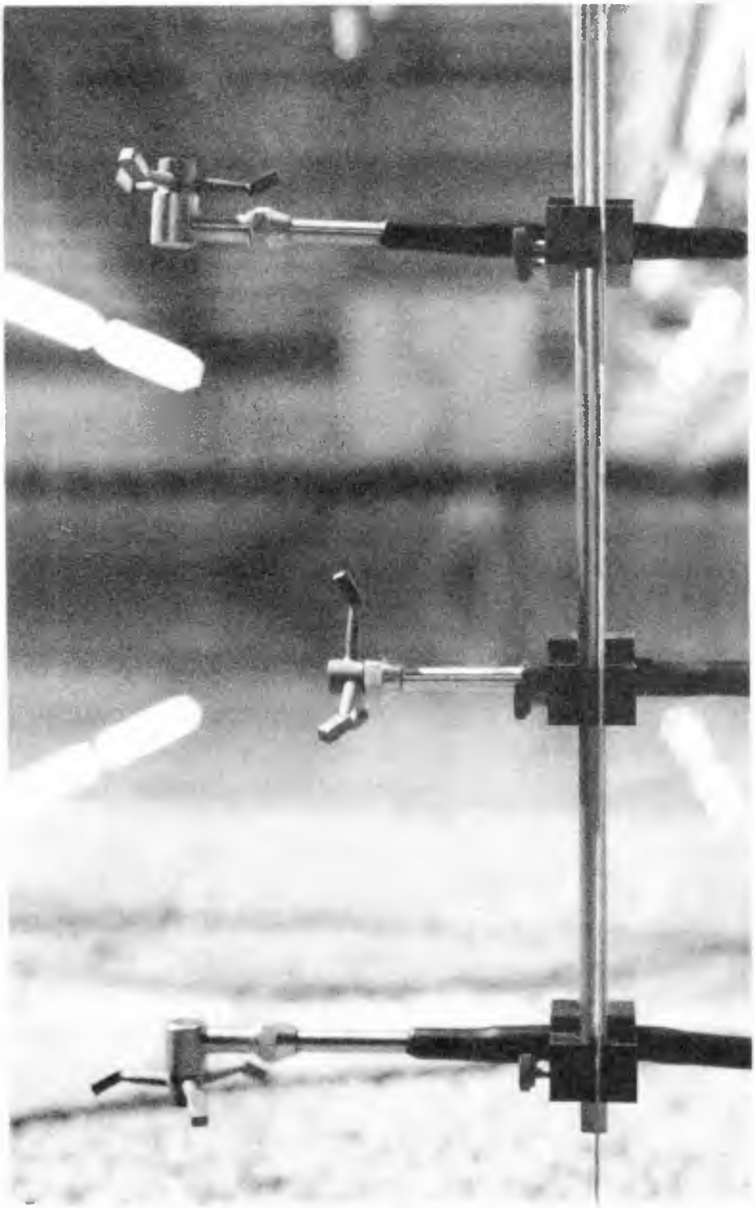

Figure 2 **Photograph of the three Sontek acoustic velocimeter probes**

Figure 3 Granite roughness on the surface of the UCL shear cell

the horizontal bed before moving on to a 1-in-20 sloping plane beach. The general design and capabilities of the basin are described by Simons *et al.* (1995).

Experiments

The experiments reported here were performed with waves propagating orthogonally across a turbulent current above a fixed bed roughness. They involved:

a) 2 wave sequences generated from Jonswap spectra with peak frequencies of 0.4 Hz and significant wave heights of 0.15m and 0.18m; and

b) 5 regular wave conditions, with periods in the range 1.7s to 3s and heights between 0.18m and 0.26m.

Each test condition was repeated with the velocity measuring system positioned at different heights above the bed to allow vertical velocity profiles to be determined. For the tests on regular waves, between 150 and 200 wave cycles were recorded at each position - from which ensemble averages were processed; for the random waves, the sequences lasted 20 minutes.

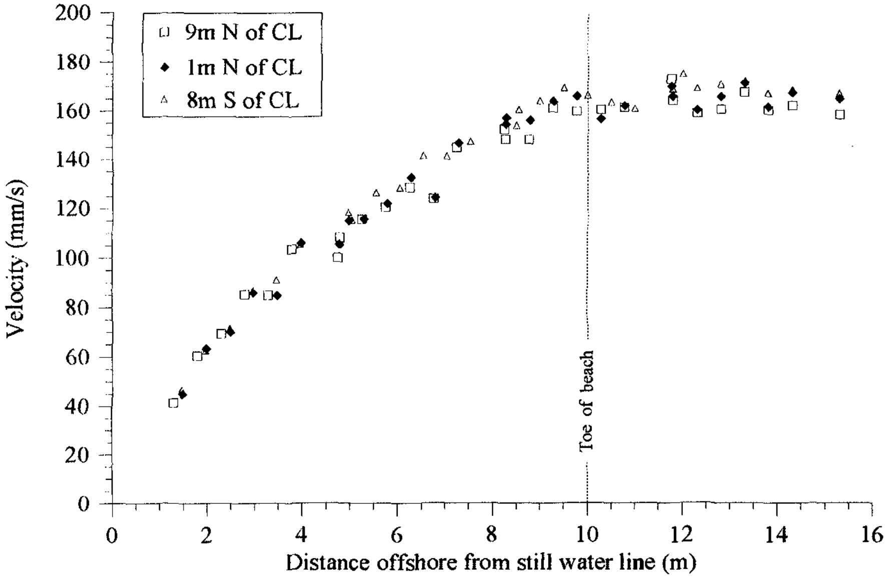

Figure 4 **Graph showing the distribution of longshore current across the beach in the central test region of the basin.**

The longshore current superimposed on the waves had a maximum velocity in the deep water region of approximately 0.14 m/s, reducing parabolically up the plane beach - see **fig.4**. At each position on the basin centreline, the vertical profile was logarithmic and demonstrated that the boundary layer was fully developed. This particular current setting is one of the standard reproducible conditions for the UKCRF established during initial evaluation work on the Facility. Test conditions and results are listed in **Table 1**.

MEAN CURRENT PARAMETERS

Current Alone

TEST	T (s) [a]	H (m) [b]	U_{bar} [c] (m/s)	Z_0 [d] (m)	τ_c (N/m^2) Log layer	Shear cell
0410953	--	--	0.119	6.24 E-4	0.086	0.079

Regular Waves & Current

TEST	T (s) [a]	H (m) [b]	U_{bar} [c] (m/s)	Z_a [d] (m)	τ_m (N/m^2) Log layer	Shear cell	WCI [k] parameter y = $\tau_m/(\tau_c+\tau_w)$
0310951	1.70	0.213	0.122	3.33 E-3	0.254	--	0.047
0610953	2.10	0.219	0.125	4.52 E-3	0.364	0.264	0.057
0210951	2.45	0.256	0.119	6.19 E-3	0.395	0.365	0.064
0610951	2.70	0.262	0.121	3.48 E-3	0.258	0.263	0.058
0410951	3.00	0.260	0.116	4.73 E-3	0.284	--	0.064

WAVE PARAMETERS

Regular Waves Alone

			Crest				Trough			
TEST	T (s) [a]	H (m) [b]	U_{bed} [e] (m/s)	a/Z_0 [f]	τ_w [g] (N/m^2)	WCI [k] parameter x = $\tau_c/(\tau_c+\tau_w)$	U_{bed} [e] (m/s)	a/Z_0 [f]	τ_w [g] (N/m^2)	WCI [k] parameter x = $\tau_c/(\tau_c+\tau_w)$
0310952	1.70	0.199	0.331	131	6.41	0.013	0.253	100	5.31	0.016
0610954	2.10	0.177	0.409	204	7.34	0.012	0.326	162	6.30	0.013
0210952	2.45	0.275	0.406	194	7.52	0.011	0.233	111	6.09	0.014
0610952	2.70	0.254	0.435	203	9.45	0.009	0.228	107	4.36	0.019
0310953	2.99	0.243	0.451	220	10.01	0.008	0.269	131	4.38	0.019

Irregular Waves Alone

TEST	T (s) [a]	H (m) [b]	U_{bed} [h] (m/s)	a/Z_0 [i]	τ_w [h] (N/m^2)
2909952	2.24	0.152	0.130	74	1.98
2809951	2.19	0.187	0.149	83	2.32

Regular Waves & Current

			Crest				Trough			
TFST	T (s) [a]	H (m) [b]	U_{bed} [e] (m/s)	a/Z_0 [f]	τ_{max} [g] (N/m^2)	WCI [k] parameter Y = $\tau_{max}/(\tau_c+\tau_w)$	U_{bed} [e] (m/s)	a/Z_0 [f]	τ_{max} [g] (N/m^2)	WCI [k] parameter Y = $\tau_{max}/(\tau_c+\tau_w)$
0310951	1.70	0.213	0.310	124	6.08	0.937	0.237	94	4.97	0.921
0610953	2.10	0.219	0.358	176	5.70	0.768	0.290	142	5.86	0.919
0210951	2.45	0.256	0.416	187	7.97	1.048	0.187	84	4.78	0.774
0610951	2.70	0.262	0.439	197	8.76	0.919	0.210	94	4.14	0.930
0410951	3.00	0.260	0.464	237	9.69	0.960	0.266	136	4.09	0.916

Irregular Waves & Current

TEST	T (s) [a]	H (m) [b]	U_{bed} [h] (m/s)	a/Z_0 [i]	τ_w [h] (N/m^2)
2909953	2.23	0.153	0.128	73	1.97
2909951	2.20	0.186	0.156	88	2.37

[a] T_{13}, established from phase locking wave probe 3. (Data file B)
[b] H_{13}, established from wave probes 2 & 3. (Data file B)
[c] Depth averaged velocity.
[d] Established from log layer.
[e] At z'=35mm. (Ensemble average data file C)
[f] a calculated as $U_{bed}/(\pi/\text{half period})$.
[g] Established from shear cell.
[h] RMS of time series. (Data file A)
[i] a calculated as $U_{bed}/(2\pi/\text{wave period})$.
[k] WCI parameters from Soulsby *et al*. (1993)

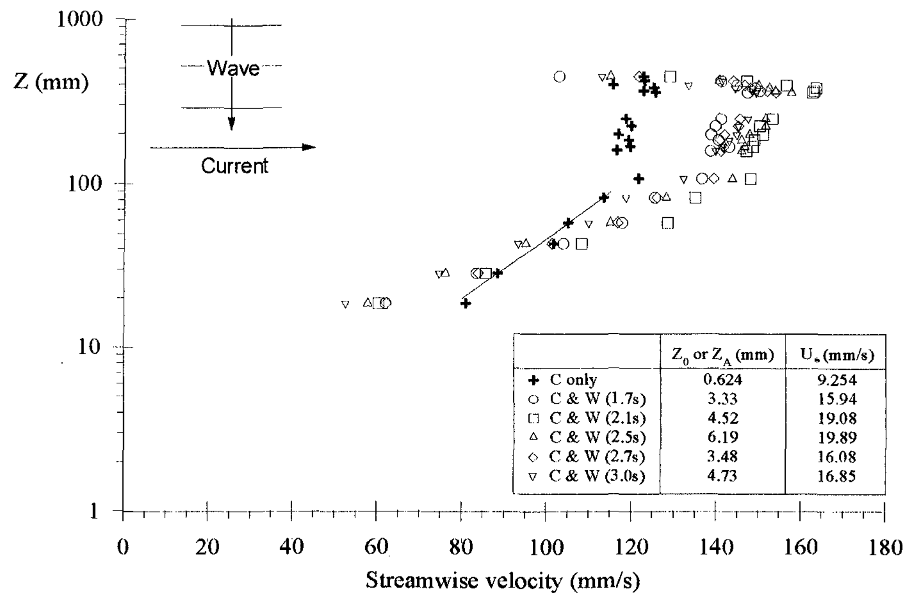

Figure 5 **Longshore current mean velocity profiles: u v $\log_e z$**
Current alone and with waves superimposed.

Results

Analysis of the logarithmic mean velocity profiles for the current alone suggested a bed roughness, ks, of 18.7mm. When orthogonal (or oblique) waves were superimposed, the logarithmic profiles (**fig.5**) showed the expected increases in mean shear stress and apparent bed roughness from their values for current alone. It was also noted that the average-over-depth flow rate was slightly higher at the offshore measuring position when the waves were present. This was attributed to the non-linear wave-current enhancement of mean shear stress being greater in shallow water than in the deep water region, thereby producing a greater resistance to the longshore current inshore on the 1-in-20 beach and thus redirecting the flow out towards the deeper water - where the present measurements were made.

Table 2 shows a comparison between the observed mean longshore shear

Test Data			Model predictions for τ_{wc} Nm^{-2}							
T s	τ_c Nm^{-2}	τ_{wc} Nm^{-2}	F 84	MS 90	HTT 91	DSK 88	OY 88	CN 86	S 91	N 92
1.7	0.09	0.25	0.16	0.14	0.22	0.16	0.15	0.20	0.20	0.20
2.1	0.09	0.36	0.19	0.17	0.26	0.18	0.15	0.22	0.25	0.23
2.5	0.09	0.39	0.17	0.16	0.23	0.17	0.14	0.19	0.22	0.20
2.7	0.09	0.26	0.18	0.17	0.24	0.17	0.13	0.19	0.23	0.21
3.0	0.09	0.28	0.19	0.18	0.25	0.19	0.13	0.20	0.24	0.18

Table 2: Mean bed shear stress τ_m: comparison of measurements from regular wave tests with predictions from 8 theories.

stresses τ_{wc} deduced from the logarithmic velocity profiles and predictions from a number of wave-current models. τ_c was measured for the current on its own. The values from Davies *et al.* (1988), Fredsoe (1984), Huynh-Thanh & Temperville (1991), Myrhaug & Slaattelid (1990), and O'Connor & Yoo (1988) were all deduced from the parameterised versions of those models presented by Soulsby *et al.* (1993) and discussed above; this was particularly helpful for the fully numerical models which would otherwise have been inaccessible. The values from Coffey & Nielsen (1986), Sleath (1991), and Nielsen (1992) were calculated (more-or-less) directly.

Test data			Model predictions for za							
T s	z0 mm	za mm	F 84	MS 90	HTT 91	DSK 88	OY 88	CN 86	S 91	N 92
1.7	.63	4.73	3.82	3.09	6.92	3.65	3.45	6.04	9.12	5.7
2.1	.63	3.48	4.63	3.81	8.29	4.43	3.04	6.47	12.3	6.68
2.5	.63	6.19	4.96	4.35	8.13	4.75	3.13	5.55	11.7	6.24
2.7	.63	4.52	4.92	4.35	8.00	4.71	2.81	5.40	12.4	6.34
3.0	.63	3.33	6.31	5.67	9.89	6.06	3.20	5.93	14.5	6.97

Table 3: Apparent bed roughness k_a: comparison of measurements from regular wave tests with predictions from 8 theories.

However, these three models are intended primarily to predict the enhanced bed roughness assuming an appropriate value for wave-current shear stress. To deduce the predicted shear stress in these cases, it has been assumed that the mean-over-depth velocity is as measured for the wave-current tests, and also that the velocity profile remains logarithmic across the full flow depth. Then, starting with an initial guess for shear stress, it is possible to calculate a first estimate for apparent bed roughness from an integrated form of the logarithmic boundary layer equation. An improved estimate for shear stress can then be found, and repeated iteration used to produce solutions both for apparent roughness and for mean shear stress.

Table 3 gives a similar comparison to that described above, but now looking at the apparent bed roughness. The predictions have been calculated, again assuming fully logarithmic velocity profiles and also that the mean-over-depth velocity is as measured in the combined wave-current flow. This was done to allow flows to be compared "like-for-like" and to overcome the problem of the local flow rate having been altered by the redirection of the longshore current (as discussed above). In order to obtain these data for each case, it was necessary to integrate the velocity profiles manually - taking into account the additional Eulerian mean flow taking place above Still Water Level through the wave crest. A typical example, showing a curve-fit through the scattered ADV data from which the mean-over-depth velocity was calculated, is shown in **fig.6**.

The first thing to note from these two tables is that the apparent bed roughness and mean shear stress have, as the models all predict, both increased when the waves are superimposed. That there is not a steady increase with relative wave strength can be attributed to the observation that the longer period waves have become non-linear with significant secondary crests. However, even when looking at the 1.7s and 2.1s period tests, it can be seen that there is a wide range of predictions and that no single model stands out as ideal.

Turning to the wave-induced stresses, friction factors for the regular wave tests calculated from ensemble averaged wave-induced velocities and shear stresses showed no visible change when the current was superimposed, so confirming UCL's earlier results.

Continuous time-series of velocities and shear stresses from the random wave tests were analysed half a wave cycle at a time to produce some hundreds of independent values of friction factor through each sequence of irregular waves **(fig.7)**. Values were calculated for a specific half-wave period, determining the amplitude between consecutive trough and crest - of wave-induced shear stress from the shear cell, and of velocity from ADV measurements outside the wave boundary layer.

Again, these showed that for the range of test conditions possible in the UKCRF

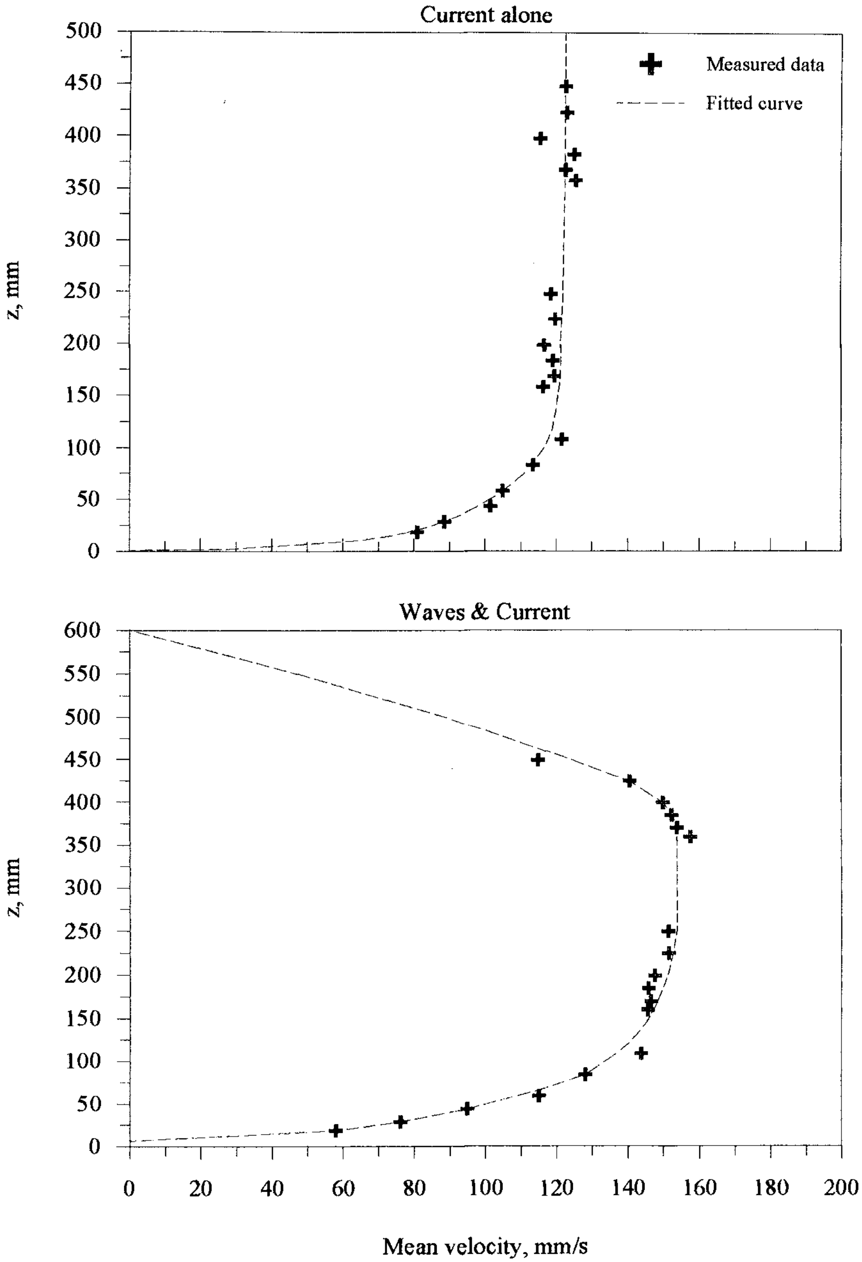

Figure 6 **Mean velocity profiles for:**
a) current alone, b) current + wave (T=2.5s, H=0.2m)

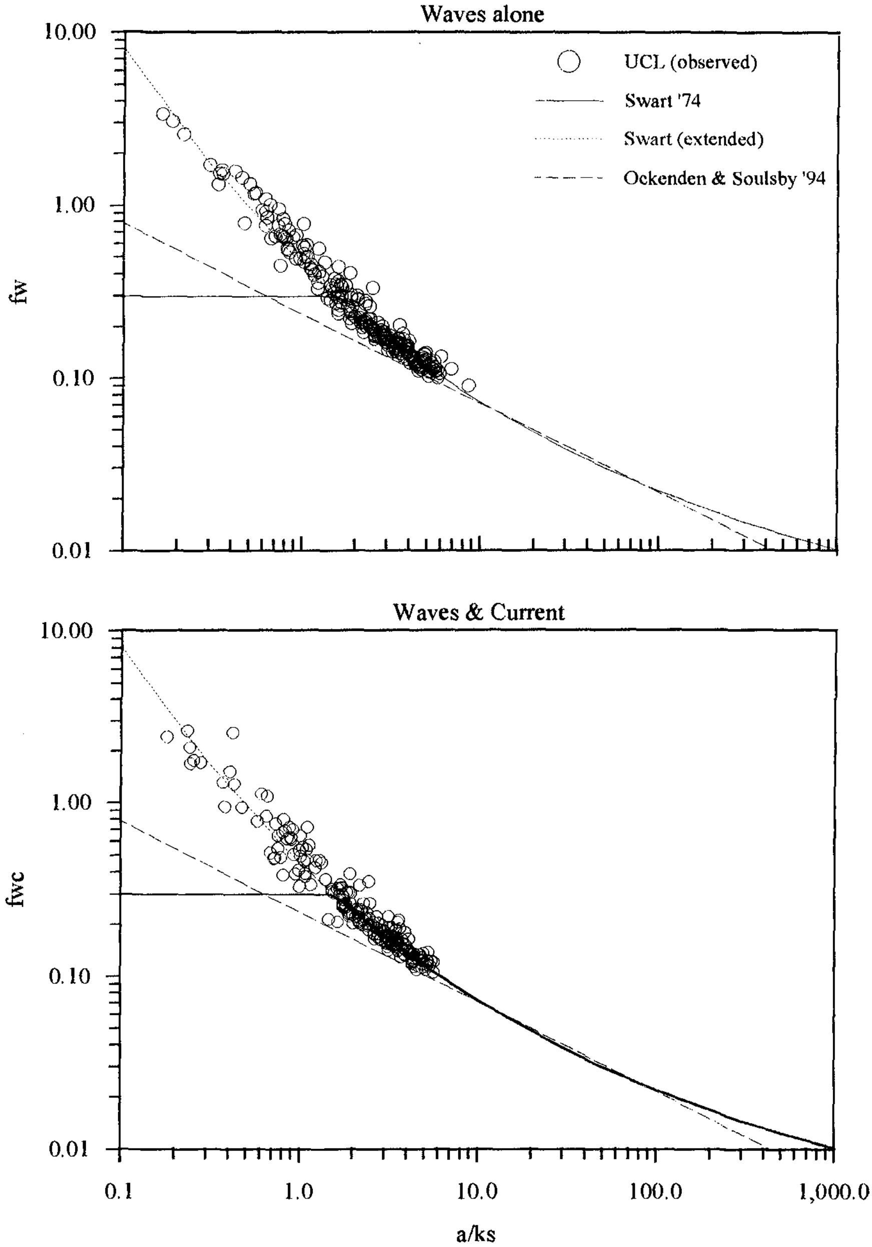

Figure 7 **Friction factor calculated from each half wave cycle: Random wave sequence: Tp=2.5s, Hs=0.15m**

there is no discernable increase in friction factor (and hence no effect on the wave-induced bottom shear stress) when a current is superimposed. However, they did confirm that Swart's (1974) formula for friction factor gives a good estimate, for waves alone or with an orthogonal current added, even at very low a/k where a constant value has sometimes been proposed. Comparison with the power law approximation proposed in Ockenden and Soulsby (1994) is also encouraging for the practical range $5<a/k<100$ although this appears less accurate at low values of a/k and cannot be correct at high a/k where the friction factor should tend to a constant value for a quasi-steady current.

If we now consider what enhancement of wave-induced shear stress (or friction factor) is to be expected when a current is superimposed, it seems that none of the models actually predicts any significant enhancement under the conditions being investigated. This is because the wave boundary layer only starts to be modified when the current-induced mean shear stress is of a similar magnitude to the wave-induced stress, and this can only be achieved in the laboratory if mean flow velocities are impractically high or the waves are so small as to be dominated by viscosity and surface tension. So the consistent behaviour of the waves whether with and without the longshore current is indicating that this aspect of wave-current theory is valid.

Conclusions

For a longshore current, mean shear stress and apparent bed roughness are both increased significantly by the addition of relatively strong orthogonal waves. Predictions from the wave-current models vary significantly, although the Davies *et al.* (1988) and Fredsoe (1984) theories appear most consistent with the present data.

Swart's (1974) formula for wave friction factor gives excellent agreement with the values measured by the shear cell for both regular and irregular waves.

The addition of a relatively weak longshore current has no effect on the bottom shear stress generated by waves on a rough bed.

The UCL shear cell is capable of measuring mean and oscillatory bottom shear stresses in a large-scale three-dimensional flow field.

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