CHAPTER 42

Bottom Shear Stresses under Random Waves with a Current superimposed.

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Abstract

This paper describes experiments performed with the UCL shear plate device to make direct measurements of the bottom shear stress vector under the action of combined waves and currents. The three corresponding velocity components have also been recorded simultaneously, enabling the results to be expressed in terms of a friction factor. The scope of the work extends that of earlier tests on regular waves, and includes three sequences of random waves propagating above a fixed rough bed in still water and over two orthogonal currents.

The results show that, for the range of conditions considered, the addition of an orthogonal current has no discernable effect on the amplitude of the shear stress time series or on the friction factors used to characterize the complete sequence. If a single friction factor is used to describe the shear stress throughout a sequence of random waves, and if that factor is calculated from the RMS of the shear stress during the sequence scaled on an equivalent regular wave with a bottom orbital velocity amplitude of $u_{\rm rms}$. $\sqrt{2}$, then the results agree well with earlier observations from tests on regular waves, and $f_{\rm w}$ can be predicted from standard formulae.

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Introduction

The prediction of shear stresses at the sea bed is an important requirement for coastal engineers wishing to estimate wave energy loss, current strength, and sediment transport around our coastline. These stresses are applied both by wave action and by currents, so any non-linear interaction between the two scales of motion in a combined wave-current flow makes the prediction of bottom shear stress a non-trivial task.

There are over thirty different theories that have been developed taking into account non-linear interaction when predicting bed shear stresses under combined wavecurrent conditions. Many of these have been reviewed by Soulsby et al. (1993) in a paper that also brought together existing data sets against which the behaviour of the theories could be tested. But whereas this paper concentrated on monochromatic wave conditions, other researchers have tried to address the problem of currents interacting with a random wave sequence. For instance, Lee (1987) proposed a linearization technique for bed shear stress in order to predict bottom frictional dissipation under irregular waves; and, in the light of a recent field study under random wave conditions, Black and Gorman (1994) suggested a modified form of the Christoffersen and Jonsson model. Zhao and Anastasiou (1993) have presented a more rigorous approach to the problem, deriving a theory based on the regular wave model of O'Connor and Yoo (1988) - itself built on the work of Bijker (1966). Equations were derived separately for wave-dominated and current-dominated conditions as well as for the general case, and comparisons were made with published data. Ockenden and Soulsby (1994) have considered the same problem but with the specific requirement of estimating sediment transport rates under irregular waves and currents. They put forward a simple solution based on an equivalent regular wave ($u_b = \sqrt{2} \cdot u_{rms}$, T_p = peak spectral period), and accounted for non-linear effects by adopting a parameterised version of the desired wavecurrent model as presented in Soulsby et al. (1993). And, finally, Madsen (1994) has developed a modified version of the Grant and Madsen (1979) model to be applied when irregular waves propagate over a current.

While there is increasing attention being paid to the theoretical prediction of bed friction under irregular waves on a current, experimental results from tests under combined wave-current conditions in general relate to monochromatic waves only, and relatively little work has been done under the practical case of random waves on a turbulent current. One of the reasons for this is the difficulty of making direct measurements of bed friction generated by unsteady flows, and shear stresses have often had to be deduced from modified velocity profiles or energy principles. However, Simons et al. (1992) have reported direct measurements of bottom shear stress using a novel shear plate device deployed in a large wave basin when regular waves are propagated orthogonally across a turbulent current, and the present paper extends that work to include sequences of random long-crested waves propagating across the same currents.

Wave Basin

The tests were performed in a wave basin measuring 20m by 18m, designed for a water depth of 1.5 m but with a raised central test area, 9 m by 6 m, over which the still water depth was reduced to 700 mm. This plateau area was coated with a fixed layer of sand (nominal diameter of 2 mm) to produce a uniform rough boundary with a Nikuradse roughness, k, of 1.5 mm - see Simons et al. (1992).

Ten ram-type wave generators were mounted along one wall of the basin. Each ram could be operated under independent control to produce waves with periods between 1 s and 3 s, and with heights up to 300 mm. The other three walls supported permeable beach units 2.5 m long round the perimeter of the basin. This beach system was constructed of synthetic "hairlock" sheets on a rigid frame, with a slope of 15° down to half-depth but with a vertical permeable face below that level. To avoid reflections of the relatively shallow water waves from this area, the 15° slope on the wall facing the wave generators was continued down with shingle "fill" to meet the raised bed in the centre of the basin.

Currents were introduced through a set of gate valves under the beaches in one of the side walls, flow being removed through a corresponding set of openings in the other side. The current strength was controlled by adjusting the speed of a pump which circulated water through a 2-compartment channel round the perimeter of the basin.

Instrumentation

For successful completion of the work, it was important that direct observations could be made of the shear stresses exerted on the bed of the basin by both currents and waves. A shear plate device had been developed in a preceding project exactly for this purpose, employing a circular "active" element supported on 4 thin columns and operating in sway mode in response to the instantaneous force vector. The system was described by Simons et al. (1992), and the same instrument was used in the present tests.

To determine the velocity field in the three-dimensional flow created by intersecting waves and currents, measurements were made using an ultrasonic current meter (UCM) capable of yielding three velocity components simultaneously. The transmitters on this instrument "pinged" at 100Hz, giving a response time of 1/30s and a resolution of 1mm/s in a range up to 1 m/s. The UCM was used to record the flow field immediately above the wave boundary layer (to correlate with the shear plate measurements), and up to the water surface. However, its size (with a measuring volume 15 mm in diameter) meant that it was unable to provide detailed information within the relatively thin wave boundary layer.

Run Code:	Tz (s.)	Hsig (cm)	U ₅₀ m curr. cm/s	U _{rms} wave cm/s	τ _m curr. N/m ²	τ _{rms} wave N/m ²	a/k	f _w
CU2			11.3	1.7	0.04	0.01		
CU1			20.1	2.7	0.08	0.02		
WR1P	1.28	14.5	-0.4	7.2	0.00	0.30	13.8	0.058
WRICC	1.28	14.4	10.5	7.4	0.03	0.32	14.2	0.058
WR1C	1.29	14.5	19.5	7.8	0.08	0.35	15.1	0.058
WR2P	1.49	14.2	0.7	8.9	0.00	0.36	19.9	0.045
WR2CC	-1.48	14.4	10.8	9.2	0.03	0.36	20.4	0.043
WR2C	1.50	14.7	19.7	9.6	0.08	0.38	21.6	0.041
WR3P	1.29	17.2	-0.8	8.9	0.00	0.37	17.2	0.047
WR3CC	1.29	17.2	10.6	9.3	0.04	0.37	18.0	0.043
WR3C	1.31	17.5	18.9	9.5	0.09	0.42	18.7	0.047

 Table 1: Observed waves and current test conditions

The water surface elevation was monitored over a 2m by 2m area centred above the shear plate using a square array of 16 resistance-type wave monitors. Data were sampled at approximately 100Hz on 22 channels for test runs lasting approximately 6 minutes.

Test Conditions

Three different "random" wave sequences were used (coded WR1, WR2 and WR3), all generated from a Jonswap target spectrum with peak periods of 1.3s and 1.5s - fig.1. Spectra observed at the four wave probes immediately surrounding the shear plate (fig.2) show that there were significant reflections in the basin at discrete frequencies, but these did not hinder the main objective of the research which was to correlate observed bottom shear stresses to the velocities immediately above the bed.



Figure 1 Sample of random wave sequence WR1 with strong current added.

Each wave spectral sequence was tested under three flow conditions: firstly through initially still water, secondly over a current with a mean velocity of 0.1 m/s, and finally over a current with a mean velocity of 0.2 m/s. The two currents were also tested without waves. Test conditions are listed in **Table 1**.

The wave sequences were reproducable, so that each test could be repeated with the UCM positioned at different heights above the bed. In this way velocity data were obtained at 18 positions through the flow depth for each test condition, while at the same time recording bottom stresses and wave surface elevations as a check on repeatability. The wave signal generator was not directly synchronised with the data recording system, so comparison between time-series from different tests required a small manual time-shift.



Figure 2 Spectra measured at 4 wave probes close to the shear plate.

The repeatability of the wave sequences was confirmed by the ease with which it was possible to overlay the time-series from tests with waves alone and those with orthogonal currents superimposed - as in **fig.3**.

Analysis

Because of the characteristics of the shear plate, it was necessary in the initial analysis of observed "shear stresses" to correct for the wave-induced pressure on the edge of the active plate. Under regular wave conditions it is possible (assuming an appropriate wave theory) to infer the pressure field across the bed of the basin from the fluid acceleration at a single point just outside the wave boundary layer above the centre of the plate. This procedure becomes more questionable under



Figure 3 Wave-induced velocities and shear stresses for random waves: a) in still water, b) with weak current, c) with stronger current.

irregular wave conditions, and in the present tests the calculation was simplified by taking the pressure gradient to be constant across the whole plate area.

It was also possible to apply a further correction to account for the pressure/inertia force being applied to the sand grain roughness attached to the plate. Although this force is a real effect, acting to generate sediment transport and dissipate wave energy, its consequences are far greater in laboratory scale experiments (with the ratio of wave length to grain diameter approximately 10^3) than in the field (ratio

greater than 10^5), and might distort the interpretation of bottom forces. However, it was largely this force component that gave the "shear stress" a significant phase lead over the near-bed velocity.

Analysis of the random wave tests was performed both wave-by-wave, comparing maximum and minimum shear stresses and velocities during each wave crest and wave trough, and also in terms of the RMS of these quantities for the complete wave sequence (neglecting the first 20s start-up period), measured under the three different current conditions.

Results

Table 1 summarises results from the 11 test runs considered in the present paper, recording the changes in wave characteristics induced by the addition of currents, and vice versa. The effect of adding random waves to the mean flow was less significant than in the earlier tests using regular waves, but from the mean velocity profiles (fig.4) it was still possible to discern a reduction in velocity in the outer flow, with a corresponding increase closer to the bed. Experimental procedures meant that measurements at different heights above the bed for the same current flow were carried out on different days, so the scatter in mean velocity data can probably be attributed to the difficulty in resetting the current. The scale of the alteration in mean velocity profile can be judged from the negligible change in mean bed shear stress in the current direction sensed by the shear plate when the waves were superimposed.

The friction factor f_w and a'_k ratio were both calculated from the root mean square properties of the full random wave sequences. The equivalent regular wave used in the normalisation procedure was chosen to have the period of the spectral peak T_p and an amplitude yielding the same RMS variation as that recorded in the random wave sequences:

$$f_{w} = \frac{\tau_{rms}}{\frac{1}{2}\rho(u_{rms}\sqrt{2})^{2}} : \frac{a}{k} = \frac{u_{rms}\sqrt{2}.T_{p}}{2\pi k}$$

Fig.5 shows these values of friction factor in comparison with previous data and theories for predicting wave-induced friction. The agreement is very good, and suggests that the use of $u_{\rm rms} \sqrt{2}$ as the scaling velocity is an appropriate choice. It is also apparent that the data from all 9 tests lie very closely clustered and thus the addition of the two currents has made no significant difference to the wave-induced shear stress. Such a lack of enhancement is in agreement with the earlier results using regular waves (Simons et al. 1992) and with the work of Arnskov et al. (1993).



Figure 4 Mean velocity profiles for current alone and with random waves added.

While it is sometimes helpful to be able to characterise a random sea in terms of regular wave parameters, it is more important in assessing sediment transport to be able to predict particular "events" when the wave-induced shear stress exceeds that needed to initiate movement of the seabed material. To give an insight into the wave-by-wave behaviour of random waves, each of the present sequences of velocities and shear stresses was considered as independent half-cycles (between velocity zero-crossings). Friction factors were calculated from the half-cycle amplitude of shear stress (between consecutive maxima and minima) and the corresponding amplitude of wave-induced velocity, and a typical data sample is shown in fig.6. This method avoided the anomalous results caused by long waves if absolute maximum and minimum values were used in the calculations, when significant shear stresses could apparently be induced by infinitesimally small velocity fluctuations. It was also decided to ignore all values for waves with an amplitude less than 1.5 mm, as this was not felt to be within the measuring accuracy of the UCM.

Fig.7 shows the friction factors produced from one of the random wave sequences,



Figure 5 Variation of friction factor with relative bed excursion for random waves with/without current superimposed: (uses equivalent wave velocity $u_{rms}\sqrt{2}$)

firstly propagating through still water, then with the weaker current superimposed, and finally with the stronger current flowing. The first thing to note is that for low a/k, the friction factors are greater than predicted by theories for fully rough turbulent flow, but that as a/k increases, so the friction factor falls back in line with those formulae - Soulsby et al. (1993) for instance. While the underprediction of f_w at low a/k is at first sight worrying, it can almost certainly be attributed to the relatively low oscillatory Reynolds numbers [ua/b] associated with these waves, when viscous effects are to be expected. In fact, the trend line formed by the scattered data lies parallel to (and almost exactly a factor of 2 above) the prediction for completely laminar flow over a smooth bed when the friction factor is given as:

$$f_w = \frac{2}{\sqrt{(Re)}} = \frac{2}{\sqrt{(ua/v)}}$$



Figure 6 Sample of shear stress and velocity data used to identify friction factors.

Much of the data lies in the rough transitional flow regime, and these values are not out of line with the observations of Kamphuis (1975) for similar conditions.

The main aim of the project was to identify what effect the addition of an orthogonal current would have on the bottom friction, and it is clear from fig.7 that all three sets of data have very similar distributions, implying that the current has caused no obvious change. The same lack of sensitivity to the addition of an orthogonal current was also found for the other two random wave sequences, and confirms the results discussed above for the friction factors based on an equivalent regular wave representative of the complete test run, namely, that the current has little effect.

Although these results indicate that the presence of longshore currents can be ignored when considering wave energy dissipation in the onshore direction, it



Figure 7 Friction factors for each half-cycle during random wave sequences: a) in still water, b) with weak current, c) with stronger current added.

should be noted that Lodahl et al. (1994) have recently reported results from tests over a smooth boundary. These suggest no increase in oscillatory shear stress when weak currents are added, but that friction factors do increase with the addition of currents at Reynolds numbers very much greater than those reported here. It is not unreasonable to expect that the interaction between a fully turbulent wave boundary layer and a turbulent steady current boundary layer is likely to be qualitatively different from the corresponding interaction at the low Reynolds numbers prevailing in the present tests.

Summary

Tests have being performed with 3 different sequences of Jonswap spectrum random waves, and direct measurements have been made of the bottom shear stresses with the UCL shear plate.

Friction factors have been calculated to represent the complete test sequence, using the RMS of the shear stress. When scaled on an equivalent regular wave with bed orbital velocity $u = u_{rms} \sqrt{2}$ and period = T_p , the results correspond to standard predictions for fully rough turbulent wave-induced motion.

Friction factors have also been calculated for each half-cycle during the tests. These reflect the transitional regime in which the data lie, at low a/k indicating higher values than predicted for fully rough turbulent oscillatory flow, but giving good agreement at higher a/k, where the flow approaches the fully turbulent regime.

For the three random wave spectra tested, the addition of a current was found to have little effect either on the wave-induced velocities near the bed or on the oscillatory shear stresses and friction factors.

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