# CHAPTER 25

### The Influence of Currents on Wave Attenuation

Richard R. Simons 1 Anthony J. Grass 2 Andreas Kyriacou 3

Measurements have been made of wave height decay in a rough bottomed flume for waves alone and for waves combined with 3 following currents. Tests have also been carried out to quantify energy dissipation at the sidewalls under these conditions. Results show that waves attenuate less rapidly when propagating on a following current, with a corresponding reduction in wave-current friction factor. A simple method is suggested by which wave attenuation in the presence of following and opposing currents can be predicted.

#### Introduction

Coastal Engineering is dependent on a detailed knowledge of wave climate for the design of coastal structures and defences, and in the prediction of sediment transport. An important step in obtaining this information is to transform available offshore wave data for application to coastal conditions. This procedure has to take into account shoaling, depth refraction, diffraction, frictional energy losses, and the action of currents. Apart from additional refraction, currents have two other important effects on waves. The first is that as the waves propagate onto a region of flowing water they experience a change in wave length, height, and orbital velocity distribution. These changes are local and to some extent reversible. The second effect is that the shear stress at the seabed, and hence the rate of wave energy dissipation, is altered significantly. This causes a permanent change which propagates with the waves until they break on the shore.

A number of papers describing field observations (i.e. Battjes, 1982) have commented that wave heights often increase when waves are propagating on a following current, and, conversely, that they decrease in the presence of an

<sup>&</sup>lt;sup>1</sup>Lecturer, Civil Engineering Dept, University College London England

<sup>&</sup>lt;sup>2</sup>Reader, Civil Engineering Dept, University College London England

<sup>&</sup>lt;sup>3</sup>Research Assistant, University College London England

opposing current. At first sight, these effects are anomalous in that all theories of "local" wave-current interaction predict that the stretching effect of a following current on waves reduces their height. However, a possible explanation is provided by the results of Kemp and Simons (1983), who found that attenuation rates go down if waves propagate with a following current, but that attenuation increases when waves move onto an opposing current. Data showing similar trends have also been published by Brevik and Aas (1980) and Asano at al (1984).

The purpose of the research described in this paper is to provide more experimental data for the precise determination of wave attenuation and boundary shear stresses under combined waves and currents, and to suggest a simple method by which the observed results can be predicted for any particular relative current strength in terms of a wave-current friction factor.

### Experiments

The main set of tests were performed in a flume 610mm wide and 30m long, with a still water depth of 300mm. The sides of the flume were of smoothly painted wood, incorporating glass windows at regular intervals. The bed was evenly covered with a single layer of 10mm angular limestone chippings, producing a Nikuradse roughness of approximately 25mm, close to that found in the work of Kemp and Simons (1983). These large roughness elements had a critical velocity in excess of Im/s, and thus remained immobile without the need to be glued down under any of the conditions considered in the present study.

Waves were generated by a flap-type paddle supported from above and pivoted about a point below bed level. This arrangement allowed the recirculating current flow to pass beneath the paddle within the existing channel cross section, although it was found necessary to install a duct to carry the flow downstream of the paddle before combining the current with the waves. An 0.5m length of chicken wire acted as an excellent filter for unwanted waves and turbulence in this region. At the far end, the beach was constructed of a light metal framework covered with 25mm thick permeable sheets of a woven nylon. It sloped at  $6^{\circ}$  to the horizontal.

Preliminary velocity measurements were made with a propeller meter at positions along and across the flume to determine the influence of secondary flow cells, sidewall boundary layers, and the developing bottom boundary layer. These tests were carried out for the currents alone and for combined waves and currents, taking care to reject unreliable measurements in regions where the flow was subject to reversal. The detailed velocity field was measured at a section midway along the test length of the flume using a single channel laser Doppler anemometer (LDA). This provided mean velocities, turbulence intensities, and orbital velocities at up to 30 points through the vertical, the measurements being concentrated in the highly turbulent nearbed layer. The distribution of Reynolds stress was obtained from a twochannel LDA and used to establish the mean bed shear stress.

Wave attenuation and changes in mean water level were measured by resistance type wave probes traversed in 100mm steps through four 2m blocks spaced out along a 22m length of the flume. This made it possible to identify the pattern of reflected waves and to fit an exponential decay curve through the underlying incident wave heights.

The tests were conducted in a water depth of 300mm, using wave periods of 0.7s and 1.0s; such waves fall into the "intermediate" classification, with D/L of 0.40 and 0.22 respectively. Four wave heights were investigated for each period, giving bed orbital velocities in the range 10mm/s to 70mm/s. Scaled against the large bed roughness used in these tests, the relative bed orbital amplitude,  $a/k_s$ , was generally less than unity. Four different current conditions were considered in combination with these waves, namely, no current, and following currents with mean-over-depth velocities of 75mm/s, 190mm/s and 250mm/s. The test parameters are set out in Table 1.

## <u>Results</u>

### Hydrodynamics:

Before considering the effects of currents on the wave surface properties, it is worth noting that the hydrodynamics of the combined waves and currents were very much as found in preceding studies of a similar nature (i.e. Brevik and Aas, 1980; Kemp and Simons, 1983). For each of the three steady currents, the mean velocity profiles showed that there was a clearly identifiable logarithmic region whose slope was increased by the superposition of waves of increasing height. This implied an increase in mean bed shear stress, and also of apparent bed roughness calculated from the  $z_0$  zero velocity intercept, when waves were added. A comparison between these results and the predictions of a number of mathematical models has recently been presented by Simons et al. (1988). It should be noted that the results were based on von Karman's constants in the range 0.33 to 0.35. These values of kappa, significantly less than the classical figure of 0.4, were calculated from bed shear stress derived from the direct Reynolds stress measurements.

With the waves propagating through still water, without any current, orbital velocities were closely described by 2nd order Stokes wave theory down to the edge of a very thin boundary layer, reflecting the low  $a/k_s$  ratios under consideration. However, the addition of a turbulent current produced a significant increase in wave boundary layer thickness - see figure 1. Reynolds stresses were also changed under the combined flow conditions: whereas for the currents alone there was a linear decrease from the maximum value at the bed out to the edge of the boundary layer, when the waves were added u'v' actually decreased in the nearbed region, producing a maximum at the outer edge of the

RUN	H (mm)	L (mm)	<sup>u</sup> b (mm/s)	a/k <sub>s</sub>	u (mm/s)	α m <sup>-1</sup>
T=0.7s RDWA1 RDWA2 RDWA3 RDWA4	15.5 19.3 22.5 23.0	755 760 760 760 760	9 11 10 10	0.06 0.07 0.06 0.06	0 0 0 0	11.8 11.2 10.8 11.5
RIWA1 RIWA2 RIWA3 RIWA4	19.2 31.1 40.3 50.7	1352 1388 1380 1380	32 47 63 78	0.28 0.42 0.56 0.69	0 0 0 0	7.6 7.5 9.6 10.6
T=0.7s RDWCW1 RDWCW2 RDWCW3 RDWCW4 T=1.0s	14.1 18.4 21.1 22.6	847 847 847 847	11 13 14 17	0.06 0.08 0.09 0.11	81 81 81 81	8.1 8.6 8.8 8.2
RIWCW1 RIWCW2 RIWCW3 RIWCW4	19.6 29.5 38.5 50.5	1512 1512 1512 1512 1512	25 39 58 71	0.20 0.31 0.59 0.72	70 77 74 74	6.4 5.8 7.8 8.3
T=0.7s RDWCM1 RDWCM2 RDWCM3 RDWCM4 T=1.0s	11.8 15.0 17.2 18.2	1000 1000 1000 1000	12 15 16 15	0.06 0.08 0.08 0.08	191 195 192 197	2.9 2.2 1.4 4.8
RIWCM1 RIWCM2 RIWCM3 RIWCM4	13.5 22.7 30.5 40.7	1664 1664 1664 1668	23 35 47 61	0.17 0.26 0.35 0.45	194 197 197 197	3.7 5.4 6.0 6.5
T=0.7s RDWCS1 RDWCS2 RDWCS3 RDWCS4 T=1.0s RIWCS1 RIWCS2 RIWCS3 RIWCS4	9.9 12.9 15.1 16.3	1065 1065 1065 1065	13 15 16 15	0.05 0.06 0.06 0.06	253 252 252 252 250	3.2 4.1 3.9 3.2
	12.0 20.1 27.7 36.9	1751 1751 1751 1751 1751	21 34 44 56	0.11 0.18 0.24 0.30	250 253 251 247	5.9 6.2 6.9 6.2

Table 1: Test Parameters and Observed Attenuation Coefficients.



logarithmic layer, some 35mm above the bed.

#### Sidewall Tests:

The objective of the main test programme was to investigate the rate of attenuation of waves propagating over a following current, and to compare the results with those from waves in still water. The tests were carried out in a relatively narrow laboratory flume, and in order for the results to be applicable to real sea conditions it was necessary to take into account the energy dissipation at the flume sidewalls. For the case of waves alone in a smooth walled channel, Hunt (1952) presented a theory apportioning dissipation between bed and sidewalls for any chosen aspect ratio. Wave height decay was shown to be exponential, in the form:  $H = H_0 e^{-\alpha X}$ , with the attenuation coefficient,  $\alpha$ , given as:

$$\alpha = \frac{k}{B} \sqrt{\left(\frac{T \upsilon}{\pi}\right)} \left(\frac{Bk + \sinh 2kD}{2kD + \sinh 2kD}\right)$$

Here, B is the channel width, D the depth of water, and k the wave number,  $2\pi/L$ . A similar empirical formula based on dimensional analysis was later suggested by Treloar and Brebner (1970). However, the application of theories of this type to the case of combined waves and currents has not before been considered. Thus it was decided to carry out a short series of tests to quantify the influence of the sidewalls under the present conditions, and to establish whether the Hunt theory formed the basis for an appropriate correction technique.

A temporary vertical wall of plate glass was installed over a 6m length of the flume, parallel to one of the sidewalls and such as to leave a closely uniform gap of just 10mm. Waves propagating in 300mm of water through this narrow channel attenuated rapidly, due almost entirely to frictional dissipation at the sidewalls. Figure 2 shows a typical exponential decay of wave heights for one of the tests with no current present, indicating that the Hunt theory predicts the attenuation coefficient to well within 15%, although with a consistent trend to underpredict. The modified form developed by Treloar and Brebner produced values even lower. Similar results were found when the tests were repeated with the gap reset to 20mm.

For the tests in combined waves and currents, it was impossible in such a narrow channel to reproduce the detailed characteristics of the stronger currents found in the fullwidth flume, although acceptable correlation was achieved with the weaker current mean velocity. Despite the reflected wave pattern being amplified by the addition of the current, the results from these tests (figure 3) showed that the sidewall attenuation was reduced by approximately 15% from that for the waves alone. In this case, taking the sidewall contribution from the corresponding wave alone tests to be between 35% and 50% of the total dissipation, use of the wave alone sidewall correction produced an error of 6%. For the



Fig.2: Wave Decay under the Influence of Smooth Sidewalls: T = 0.7s; D = 300mm; u = 0; gap = 10mm.



Fig.3: Wave Decay under the Influence of Smooth Sidewalls: T = 1.0s; D = 300 mm; u = 70 mm/s; gap = 20 mm.

present work, this was felt to be acceptable.

## Attenuation:

Results from the main tests in the 610mm wide flume showed that wave heights reduced exponentially along the flume both with and without currents flowing. However, attenuation coefficients were found to decrease systematically when following currents of increasing strength were superimposed (figure 4). The same effect was found both for the waves of 0.7s and 1.0s period, and it confirmed the earlier observations of Kemp and Simons (1983), who had furthermore reported that attenuation increased when an opposing current was introduced. These observations, made in a fixed frame of reference, are relevant to those predicting wave heights under real sea conditions. However, even when expressed in terms of wave height loss per wave length, or of loss of wave action (wave energy divided by relative angular frequency), there was still a clear trend for the currents to reduce the rate of change in all the tests carried out. The possibility was examined that the changes in wave height might be the result of variations in mean velocity profile over the 22m test length of the flume rather than of modified energy dissipation. However, the preliminary velocity measurements showed that any influence of the developing boundary layer, and in particular a gradual increase in surface velocity, would tend to increase apparent attenuation and hence oppose the observed effect.

In order to simplify the presentation of the results, it was decided to follow the method first proposed by Jonsson (1966) and reassessed by Brevik and Aas (1980), and to express the attenuation rates in terms of a wave-current friction factor,  $f_{\rm WC}$ , assumed constant through the wave cycle. Neglecting the phase difference between the flow in the oscillatory boundary layer and that in the outer region, the bed shear stress is related to  $f_{\rm WC}$  as follows:

$$\tau_{\rm WC} = 1/2 \ \rho \ f_{\rm WC} \ | \mathbf{u} + \mathbf{u}_{\rm b} | \cdot (\mathbf{u} + \mathbf{u}_{\rm b})$$

where u is the depth averaged mean velocity and  $u_b$  the amplitude of the oscillatory wave-induced velocity, taken to be sinusoidal, just above the wave boundary layer. Assuming that the flow is not current dominated, the Momentum Equation,

$$dF/dx + \tau_{WC} = 0, \tag{1}$$

with  $F = 1/8 \rho g H^2 (2c_{qr}/c - 1/2) + \rho D u^2 + 1/2 \rho g D^2$ 

and  $c_{qr} = c_{qa} - u$  then becomes:

$$1/4 \rho \, \text{gH} \, d\text{H/dx} \, (2c_{\text{gr}}/c - 1/2) + \rho \, \text{gD} \, d\text{D/dx} + 1/2 \, \rho \, f_{\text{WC}} \, |\mu + u_{\text{b}}| \cdot (\mu + u_{\text{b}}) = 0$$
 (2)

The averaged Energy Equation can be treated in a similar way to give:



Fig.4: Wave Height Attenuation along the Main Test Flume.

$$\frac{1/4 \rho g H \left\{ c_{gr} + 2 c_{gr} / c + 1 / 2 \right\} u + \rho g D u d D / d x}{\mu + 1 / 2 \rho f_{WC} \left[ \mu + u_b \cos \omega t \right]^3} = 0 \quad (3)$$

Eliminating the water surface slope dD/dx between (1) and (2), we are left with a relationship between wave height attenuation and  $f_{wc}$  in the form:

$$f_{WC} = gH/2\beta \quad (c_{gr} + u) dH/dx$$
(4)

where 
$$\beta = u \cdot \mu + u_b \cos \omega t \cdot (u + u_b \cos \omega t)$$
  
-  $\mu + u_b \cos t \cdot dt$  (5)

It must be emphasised that this derivation relies on the assumptions of 1st order waves, a time-invariant friction factor, significant wave action relative to the current strength, neglect of phase shifts between orbital velocities and bed shear stress, and a uniform mean velocity profile.

Considering first the results for waves alone, it was found that the friction factor continued to increase for the smaller waves as the bed orbital amplitude was reduced - see figure 5. Waves as the bed orbital amplitude was reduced - see figure 5. Values agreed closely with the expression given by Jonsson (966), and also with the trends predicted by Kajiura (968) and Kamphuis (975). In contrast, the addition of following currents caused a steady decrease in friction factor as the current strength was increased, with  $f_{WC}$  for very low bed orbital amplitudes tending towards the value of 0.01 determined from the current only tests. However, this behaviour became less pronounced for the larger waves  $(a/k_s > 1)$ . 1). Figure 5 also includes the results from the tests of Kemp and Simons (1983) where the current opposed the waves. It is interesting to note that in this case, despite the increase in observed attenuation rates when the currents were added, the corresponding friction factors were actually less than those for waves alone. This apparent anomaly was caused by the reduction in absolute wave group velocity in (4) proving more significant than the increase in attenuation dH/dx. The ratio of current strength to wave orbital velocity  $(1/u_b)$  for these tests was similar to that for the weakest following current series in the present tests, and the values of  $f_{WC}$  produced by these two very different sets of conditions agreed remarkably well with each other. This suggests that the variation in  $f_{WC}$ with relative bed orbital excursion can be characterised by a series of curves, each representing a particular relative current strength. A similar set of curves can also be generated if  $f_{WC}$  is plotted against Reynolds number (as in figure 6).

While at first sight it might seem surprising that friction factors should decrease as current strength is increased, the effect is predicted qualitatively by mathematical models of wave-current interaction such as Christoffersen and Jonsson (1985). Friction factors calculated from these models fall off from the wave alone curve for values of  $a/k_s$  less than 30, although not to such an extent as observed in the present study. The values of fwc so calculated are also insensitive to the direction of the current, whether it propagates with or



Fig.5: Variation of Friction Factor,  $f_{WC}$ , with relative bed orbital amplitude,  $a/k_s$ , for different current strengths.



Fig.6: Variation of Friction Factor,  $f_{WC},$  with Oscillatory Reynolds Number, a  $u_b/\upsilon$  .

against the waves, once again agreeing with the present observations.

#### Conclusions

An estimate of wave height attenuation for combined wave and current flows can be obtained for given bed roughness, relative current strength, and relative bed orbital excursion either by use of an empirical friction factor diagram or from one of the many mathematical models for wave-current interaction. A possible procedure might be as follows:

1. Calculate  $\beta$  from (5); 2. Derive  $f_{WC}$  from Christoffersen and Jonsson (1985); 3. Use Eqn.(4) to calculate dH/dx, and hence derive the attenuation coefficient  $\alpha$ .

For a following current, the attenuation will be reduced with increasing current strength, but for the opposing current case the attenuation might increase or decrease, depending on the relative changes in  $f_{WC}$  and  $(c_{gr} + u)$ . A decrease is likely only if the current is very strong relative to the wave group velocity, with the possibility in the extreme case of a negative attenuation rate, growth in wave height, and eventual breaking.

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