# **CHAPTER 45**

Bottom Shear Stresses in the Boundary Layers under Waves and Currents crossing at Right Angles

> Richard R.Simons<sup>1</sup> Tony J.Grass<sup>2</sup> Mehrdad Mansour-Tehrani<sup>3</sup>

## Abstract

This paper describes a two year experimental research programme investigating the influence of non-linear wavecurrent interactions on wave and current characteristics. The tests focus on the mean and oscillatory velocity components and shear stresses within the bottom boundary layer over a rough bed for cases where waves propagate at right angles to the line of the current flow. Bed shear stresses have been measured directly by means of a novel shear plate device. The aim of the research is to generate a reliable data set for use by modellers.

Results show that currents experience a significant change both in mean bed shear stress and apparent bed roughness when waves are superimposed. However, the oscillatory, wave-induced, bottom shear stress has been shown to be insensitive to the addition of an orthogonal current.

## Introduction

Recent years have seen the development of many mathematical models for predicting the boundary layer characteristics of combined wave-current flows and hence sediment transport along and across the coastline. However, the proliferation of models has not been matched

<sup>1</sup>Senior Lecturer, Civil & Environmental Engineering Dept, UCL

<sup>2</sup>Reader, Civil & Environmental Engineering Dept, UCL.

<sup>3</sup>Research Fellow, Civil & Environmental Engineering Dept, University College London, Gower Street, London WC1E 6BT. by the availability of experimental results against which they can be validated, particularly at large scale and where waves propagate orthogonally or at arbitrary angles to the current.

Published field data which include combined wavecurrent conditions generally lack sufficient control over the main parameters to provide a reliable basis for model calibration. Laboratory experiments on wave-current interaction have most often considered only the case of colinear waves and current (for example, Bakker and van Doorn (1978); Brevik and Aas (1980); Kemp and Simons (1982), (1983); Simons et al. (1988)). This situation matches that found in estuaries and in some offshore regions, but contrasts with the condition frequently occurring along many coastlines where waves propagate directly on-shore, Only Bijker (1967), and more over a longshore current. recently Visser (1986), Arnskov et al. (1991), and Sleath (1990), have considered this more complex, but extremely important, orthogonal case. Bijker's tests were restricted to measurements of shear stress deduced from observations of water surface slope in an orthogonal wave-current field, and his instrumentation was unable to determine velocity profiles above the bed. Arnskov's tests were restricted to flows over a smooth boundary and are thus hard to extrapolate to real coastal engineering situations where the bed is invariably rough, and frequently rippled. Sleath's tests were performed over a variety of rough boundaries, and he simulated waves crossing a current at right angles by oscillating a section of roughened bed across the line of a unidirectional current flowing along a laboratory flume.

Another shortcoming of earlier data has been that shear stresses have had to be implied, from nearbed velocity profiles, water surface slopes, or wave attenuation, rather than from direct measurement. It is the aim of this paper to fill a gap in existing data by providing direct measurements of bottom stress and velocity field under laboratory conditions for a range of combined waves and currents crossing orthogonally.

## <u>Wave Basin</u>

The experiments were performed in a wave basin approximately 20 m square, 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 just 700 mm. This plateau area was installed specially for these tests, and was coated with a fixed layer of sand (nominal diameter of 2 mm) to produce a uniform rough boundary.

Ten ram-type wave generators were mounted along one

wall of the basin, the other three walls supporting permeable beach units 2.5 m long at a slope of  $15^{\circ}$ . Each ram could be operated under independent control to generate waves with periods between 1 s and 3 s, and with heights up to 300 mm.

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. For the tests described here, three current conditions were investigated: zero mean flow (wave alone), 125 mm/s, and 200 mm/s.

#### Shear Plate Device

A vital element in the programme was the ability to make direct measurements of shear stress applied to the bed by the wave-current flow above. Very few attempts have been made to design such a device in the past, mainly because of the high sensitivity required to resolve the small forces involved, and the difficulty of reducing the wave-induced pressure gradient effect on the vertical faces of the structural elements. The most important results reported from such a device are those of Reidel & Kamphuis (1973), who measured friction factors for a rough boundary under a wide range of wave conditions in a two-dimensional laboratory flume. Oebius (1982) has also developed an instrument intended for deployment in the field under mobile bed conditions, while Arnskov et al. (1991) have used a hot film technique to measure shear stresses on a smooth bed.

The main criteria to be satisfied by the shear plate device during the present project were that it should be capable of measuring a 2-dimensional horizontal force vector varying rapidly in magnitude and direction, have sufficient sensitivity to resolve the relatively small shear stresses induced by the mean current, have the range to follow large wave-induced oscillatory stresses, have a surface area small enough relative to the length of a wave in the basin that spatial averaging would not significantly reduce the recorded peak oscillatory stress, have a sufficiently high natural frequency relative to the "forcing" wave frequency that inertial phase lag and resonant vibrations would be negligible, remain co-planar with the surrounding bed during test conditions, and tolerate the presence of sediment and debris in the water.

The design adopted consisted of a 0.9 mm thick, circular disc (250 mm diameter), supported on four tubular

columns, mounted flush with the surrounding bed, and deflecting sideways in a sway motion under the action of any lateral force. A clearance of under 0.5 mm was allowed between the circumference of the plate and the adjoining bed, imposing a physical constraint on the maximum possible deflection of the plate, and thus also on the measurable force for any given structural stiffness.

The horizontal displacement of the plate was measured by two eddy current transducers mounted orthogonally under the bed and positioned to monitor the movement of a small target block attached to the centre of the plate. These devices had a sensitivity of just over 0.1 microns, and operated with a working clearance of 1 mm.

Because of the finite length of the waves under test, there was a horizontal pressure gradient across the bed of the basin which exerted a significant force on the edge of the active shear plate. Although the plate was made as thin as possible to minimize the effect, pressure on the edge still contributed a significant proportion to the total force observed. The correction procedure adopted for these tests involved deducing the pressure gradient from direct measurements of orbital velocity (and hence acceleration) just above the oscillatory boundary layer. The edge force was calculated by dividing the plate into 1000 sectors, determining the radial force on each at discrete phases through the wave cycle, resolving this into the direction of wave propagation, and force integrating round the circumference.

To check whether the pressure correction was adequate, and to determine whether the shear plate was capable of measuring shear stresses to sufficient accuracy under oscillatory flow conditions, a set of preliminary tests was carried out in a wave flume. These tests were performed over a smooth bed, using a smooth active plate, for a range of wave periods between 1.0s and 1.35s. The smooth bed provided conditions for which there is a reliable theoretical solution for amplitude and phase of the bottom shear stress - calculated from the orbital velocity just outside the viscous-dominated oscillatory boundary layer.

The measured force was corrected for edge pressure, and the resulting shear stress plotted out with the theoretical shear stress and the orbital velocity through the wave cycle (fig.1). Bearing in mind that the edge pressure effect corrected for was generally far greater than the shear stress sought, there was remarkably good agreement between theory and experiment, with errors between 1% and 15%. This was felt to be satisfactory, as the shear stresses induced at the rough boundary in the main test programme were almost an order of magnitude



Fig.1 Pressure correction test for waves alone over a smooth bed: measured shear stress plotted with theoretical curve through a wave cycle.

greater than those at the smooth bed.

#### Velocity\_Measurements

To determine the velocity field in the complex threeflow, measurements were made using an dimensional ultrasonic flow meter which yielded three velocity The transmitters on this components simultaneously. instrument "pinged" at  $1\overline{0}0Hz$ , giving a response time of 1/30s and a resolution of 1mm/s in a range up to 1 m/s. However, while it was ideal for determining the instantaneous velocity vector in the upper flow, 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.

Velocities close to the bed were measured with a fibre-optic laser anemometer supported by a vertical traversing device on the overhead gantry. The measuring volume was some distance away from the optical fibre probe, and thus provided a relatively non-intrusive means of determining velocities. Tests using the LDV had to be carried out twice in order to obtain all 3 velocity components. The main set of tests had the optical fibre head set up pointing vertically downwards at the bed to measure the two horizontal components of velocity. Tests were then repeated with the optics pointing into the current, close to horizontal, so as to measure horizontal and vertical components of wave-induced velocity.

## Other Instrumentation

Wave characteristics were monitored by 16 resistancetype wave probes mounted in a rectangular grid pattern (spacing 0.5m by 0.66m) from an overhead gantry over the test area. Data from all the instruments (water surface, shear plate, anemometers) were recorded synchronously through a 32-channel data logger directly onto computer disc, together with a signal from the wave generators.

#### Results

27 different wave/current conditions were tested from combinations of four wave periods [1.1s, 1.5s, 2.0s, 2.5s.], wave heights in the range 80 mm to 190 mm, and



Fig.2 Mean velocity profiles for 2 cases of combined waves and current and for the same current alone.

three currents conditions [zero, 125 mm/s, 200 mm/s] running orthogonally to the waves. **Table 1** lists the general test parameters.

Run:	Wave Period s	Incident Wave Height mm	H at Plate	Reflex Coeff %	Current mm/s
W1P	1.49	136	125	11.8	0
W1C	1.49	135	125	25.9	200
L1CC	1.49	140	125	8.9	125
W2P	1.49	168	150	12.0	0
W2C	1.49	185	175	8.1	200
₩ЗР	1.49	98	90	18.4	0
W4P	2.02	135	165	40.0	0
W4C	2.02	138	177	39.9	200
L4CC	2.02	145	176	37.9	125
W5P	2.02	160	190	31.0	0
W5C	2.02	172	209	34.9	200
L5C	2.02	168	202	37.2	200
L5CC	2.02	170	205	37.2	125
W7P	1.11	120	122	12.0	0
W7C	1.11	118	118	25.9	200
W8P	1.11	78	76	11.5	0
W8C	1.11	78	78	10.9	200
W9P	2.48	140	152	26.0	0
L9C	2.48	130	140	24.0	200
L9CC	2.48	140	147	24.0	125
W10P	2.48	183	200	24.6	0
L10C	2.48	184	191	22.0	200
W10CC	2.48	152	162	22.0	125
L10CC	2.48	182	195	22.0	125
W11P	2.48	123	130	25.0	0
W11C	2.48				200
W11CC	2.48	150			125

Table 1: General test parameters: water depth = 700mm.

Mean velocity profiles of the two currents on their own took a form typical of most turbulent boundary layers, following a logarithmic curve through the near-bed region (within 100mm of the bed), with velocities continuing to increase but more gradually above this level up to the water surface. However, when waves were superimposed, running orthogonally to the direction of flow, there was a significant reduction in mean velocity in the upper flow, matched in most cases by an increase in the lower half of the flow (fig.2). This effect was most pronounced for the waves with longest periods (1.5s, 2.0s, 2.5s) and greatest heights, whereas the 1.1s period waves showed little change in general profile shape.

When plotted out on log-linear axes, the profiles revealed that the apparent bed roughness  $z_A$  was increased, in some cases by more than a factor of 20 times its value for current alone. The mean bed shear stress was also increased by the addition of wave action (Table 2).

Run:	Orbital Umax mm/s	Shear Vel. u. mm/s	τ <sub>mean</sub> Pa.10 <sup>3</sup>	Apparent roughness z <sub>A</sub> mm	z <sub>A</sub> / z <sub>0</sub>
CCP	0	7.03	49.0	0.05	1.0
L1CC	157	7.82	61.0	0.10	2.0
L4CC	140	7.36	54.0	0.12	2.4
L5CC	164	6.53	43.0	0.08	1.6
L9CC	212	14.40	206.0	1.15	23.0
L10CC	287	12.50	157.0	0.90	18.0
LCP	0	9.81	96.0	0.05	1
L5C	164	11.9	141.0	0.30	6.0
L9C	212	17.7	313.0	0.45	9.0
L10C	303	17.1	291.0	0.55	11.0

Table 2: Wave-current tests: mean flow parameters

As the shear plate was set up during these tests to measure the large oscillatory shear stresses induced by the wave action, relatively small mean stresses caused by the mean current were difficult to determine precisely. Nevertheless, the values obtained from the combined wave-current tests, when substituted into the "Law of the Wall", suggest that the von Karman constant  $\kappa$  lies between 0.30 and 0.50 - a wide range, but probably acceptable in view of the experimental difficulties involved in measuring both

the mean velocities and the shear stress.

Table 1 listed the basic characteristics of the waves used for each test run. All the waves lay in the "intermediate" zone, although the 1.1s period waves were close to "deep water" conditions, and the 2.5s periods approached "shallow water" status. It should be noted that the reflexion coefficients were found to be very high in many of the tests - an inevitable consequence of using waves with a length far greater than that of the absorbing beaches round the perimeter of the basin.

The most interesting tests as far as the main objective of the research was concerned were those inducing significant shear stresses at the bed of the basin. These tended to coincide with tests involving waves with the longer wave periods and lengths, and hence also with high reflexions. However, this was not considered to be a serious problem, as the majority of wave-current theories are based on the interaction of a plane oscillatory flow with a current - and a standing wave pattern induces just such a plane oscillatory flow at the bed (albeit a spatially varied one).

Data analysis included a correction to the oscillatory shear stress measurements to account for the effect of wave-induced pressure gradients at the bed of the basin. Its effect is relatively greater for the short period waves. Sleath (1991) has pointed out that an equivalent force also acts on each sand grain at the bed, and this has been taken into account in the present work.

Results from the tests with wave alone (fig.3), and those with waves and currents combined (i.e. fig.4), both showed that the oscillatory shear stress, after correction, always peaked approximately  $30^{\circ}$  before the orbital velocity. Another important observation was that the maximum shear stress was relatively unaffected by the superposition of a turbulent current - either strong or weak (see Table 3). This contrasted with the significant effect the addition of waves had on the properties of the currents.

## **Discussion**

Considering first the changes caused to the mean current profiles by the superposition of waves, the additional resistance experienced in the upper flow is something that has been reported in earlier papers on wavecurrent interaction (Kemp & Simons, 1982; Bakker & van Doorn, 1978). However, it is an effect not included in any of the present generation of mathematical models purporting to describe the wave-current process. The most likely

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Fig.3 Ensemble averaged bottom shear stress and orbital velocity in line with direction of wave propagation: wave alone W2P: H = 168mm; T = 1.49s; U = 0mm/s.



Fig.4 Ensemble averaged bottom shear stress and orbital velocity in line with direction of wave propagation: wave + current W2C: H = 185mm; T = 1.49s; U = 200mm/s.

Run:	Wave	Orb	RE	a/k <sub>s</sub>	τ <sub>max</sub>	friction
	s.	o <sub>max</sub> mm/s	$=$ $U_{max}a/v$		Pa	Iactor
W1P	1.49	142	4775	22	0.841	0.083
W1C	1.49	158	5910	25	0.902	0.072
L1CC	1.49	156	5761	25	0.792	0.065
W2P	1.49	189	8456	30	1.076	0.060
W2C	1.49	222	11562	35	1.066	0.043
W3P	1.49	104	2560	16	0.621	0.114
W4P	2.02	125	5112	27	0.626	0.080
W4C	2.02	114	4185	24	0.647	0.100
L4CC	2.02	131	5526	28	0.227	**0.027
W5P	2.02	173	9637	37	0.826	0.055
W5C	2.02	153	7538	33	0.815	0.070
L5C	2.02	163	8555	35	0.320	0.024
L5CC	2.02	164	8661	35	0.294	0.022
W7P	1.11	67	793	8	0.553	0.246
W7C	1.11	67	793	8	0.490	0.218
W8P	1.11	42	311	5	0.382	0.433
W8C	1.11	42	312	5	0.393	0.446
W9P	2.48	204	16440	54	0.435	0.021
L9C	2.48	214	18090	56	0.379	0.017
L9CC	2.48	212	17754	56	0.375	0.017
W10P	2.48	289	32992	76	0.672	0.016
L10C	2.48	300	35550	79	0.611	0.014
W10CC	2.48	260	26703	68	0.835	0.025
L10CC	2.48	277	30310	73		
W11P	2.48	177	12376	47	0.459	0.029
W11C	2.48	173	11851	46	0.485	0.032
W11CC ·	2.48	179	12657	46	0.436	0.027

Table 3: Oscillatory boundary layer parameters.

explanation is that additional Reynolds stresses are set up by the wave-induced orbital velocities, and these may be interacting with the mean current.

The increase in apparent bed roughness implied from the log-linear velocity profiles was qualitatively as predicted by all wave-current models, and, when compared with the predictions of Sleath (1991), there was good agreement in many cases. However, some of the values were found to be considerably lower than predicted by the theory, the greatest discrepancies occurring for waves with the shortest wave periods and the lowest amplitude Reynolds numbers.

Again, the increase in mean shear stress observed when waves were added to the current was as predicted by theory, and similar to that observed by Sleath (1990) in experiments on flow over an oscillating plate. It is also very much in line with that found by other researchers for a wide variety of test conditions including both field and laboratory tests.



Fig.5 Variation of wave friction factor with relative bed orbital amplitude for different wave-current combinations.

Turning now to the effect the addition of currents has on the wave characteristics, the most important finding of the work is that the maximum oscillatory bed shear stress appears to remain virtually unaltered, irrespective of the strength of the superimposed current. This is demonstrated in **fig.5**, where friction factors calculated from the maximum shear stresses under waves with and without currents are plotted out against relative orbital excursion at the bed, a/k. The tendency for observed friction factors to move above the theoretical predictions as a/k decreases may be due to some uncertainty about the velocity measurements by which they have been normalized. The effect may also relate to lower Reynolds numbers lying in the transitional rough regime where the Nikuradse roughness may vary from that determined in the tests on current alone.

The authors are presently analysing field data from a site off the south coast of Australia where conditions generally meet the criterion that waves propagate orthogonally across a coastal current (Black et al.(1992)). When available, those results will complement the present laboratory data.

## Conclusions

Currents experience a significant change both in mean bed shear stress and apparent bed roughness when waves are superimposed and propagate orthogonally across it. However, under the present test conditions, the oscillatory, waveinduced, bottom shear stress is insensitive to the addition of an orthogonal current.

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