WAVE AND CURRENT INTERACTION IN THE NEAR BED REGION.

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ABSTRACT.

The question of how waves and currents interact, especially in the near-bed region is of considerable importance in relation to sediment suspension and sediment transport. Whereas empirical relationships provide useful estimates and indications in relation to the data on which they are based, a more thorough understanding of the physical processes at work is necessary for interpreting sediment transport behaviour in a more generalized way. Clearly the conditions under which flow reversal occurs near the bed, and also the extent to which wave motion may modify the current induced turbulence in the boundary layer, are both of great interest, and these and other aspects have been included in the present study.

The research program was designed to look initially at the interaction between waves and currents in the absence of sediment, in order to define the mean velocity components, the structure of the turbulence, and the shear stresses. The study proceeded from experiments on waves alone, to waves propagating with the current and against the current. In all three cases the tests were carried out in the first instance with a smooth bed and subsequently with a rough bed consisting of two dimensional triangular slats. One of the main areas of interest was the height to which the water was disturbed above the bed when acted on by waves alone, and the comparable situation when a current was superimposed on the waves. Since the characteristics of the turbulent current were measured independently, it was possible to deduce whether there had been any interaction between the waves and the current, and also to infer what might happen to the distribution of the sediment which it was assumed would be put into suspension in the two cases. In the second stage of the research separate experiments were carried out in a standing wave channel and an oscillating water tunnel, using lightweight bed materials, in order to observe whether the inferences made from the clear water study were borne out by comparable changes in the distribution of the sediment in suspension.

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The results show that the sediment reflected the fluid motion characteristics, the sediment remaining in a band close to the bed under the action of waves alone, but rapidly dispersing when a turbulent current was introduced.

INTRODUCTION.

Comparatively little previous work has been carried out on the interaction between waves and currents, particularly near the bed. Grant & Madsen (1979) produced a theoretical analysis of combined wave and current flow over a rough boundary, predicting an increase in apparent bed roughness and shear stress when waves are superimposed on the current. A similar theory has been presented by Christoffersen (1980). Bakker & van Doorn (1978) also found an increased apparent bed roughness. George & Sleath (1979) described the cycle of vortex formation and ejection around spherical roughness elements in the presence of a weak current. The stronger downstream vortex was found to induce a weak reverse mean current just above the roughness elements.This is consistent with the observations of Inman & Bowen (1963) and Bijker, Hijum & Vellinger (1976), who both reported enhanced upstream sediment transport when a weak current was superimposed on waves. The present authors have carried out an extensive investigation on the subject of wave and current interaction, and a report of the main results may be found in Kemp & Simons (1982) and Kemp & Simons (1983). Since little information was available prior to these latter publications on the detailed flow structure under these condition, any inference between the flow characteristics and sediment in suspension has been tentative. Tunstall & Inman (1975) observed that in the case of waves alone, there was a limited thickness of the wave-induced vortex layer over a rippled bed, suggesting that sediment would be concentrated in this near bed layer. Bijker (1980), using first order wave theory and the assumption of a logarithmic profile, has formulated an expression for sediment concentration under waves and currents. The expression however contains a coefficient which is dependent on the wave motion and the bed roughness.

APPARATUS, INSTRUMENTATION AND ANALYSIS.

The investigation, and the apparatus used for the study of waves and currents in the absence of sediment, are described in the paper by Kemp & Simons (1982). This part of the work was carried out in a channel 14.5m long, 457mm wide and 690mm deep, with provision for flow in either direction and wave generation by a bottom-hinged paddle at one end. Two bed conditions were used in these tests. The first consisted of a smooth metal surface coated with gloss paint, and the second consisted of 5mm high triangular wooden strips stuck across the channel width and spaced at 18mm centres along the line of flow. The latter was chosen so as to generate a rough turbulent boundary layer both with the unidirectional current, and also with the larger waves in the absence of a current. It was also of similar geometrical form to that used by Jonsson & Carlsen (1976) in their tests in an oscillating water tunnel. The height and spacing of the roughness elements also came within the range of possible ratios of height to length found in natural sand ripples. Fluid velocities were measured using a laser-Doppler anemometer, and the analysis of turbulent and wave-induced velocities was carried out by an on-line PDP8E minicomputer. The computer was programmed to produce ensemble average velocities, Reynolds stresses and wave elevation data. The cycle was sampled at 200 separate phase positions with up to 250 observations at each position. Measurements were made at up to 30 points in the vertical.

Measurements of wave attenuation and reflection were included in the program. In the case of waves opposing the current the current had to be introduced at the beach end of the channel. In order to avoid jetting and turbulence due to the presence of the beach, a wave absorbing device consisting of a slightly sloping metal plate submerged a short distance below the still water level, proved very effective. The device is referred to in Kemp & Simons (1983).

Observations of the behaviour of various lightweight sediments under the action of standing waves, and planar oscillatory motion, were carried out in a rocking channel which produced standing waves of comparable period to that in the water tunnel, which had a natural period of 2.3 seconds. The water tunnel could produce oscillations of different amplitudes, and in addition a current could be imposed in one direction, of variable strength. The materials investigated included various grades of pumice, anthracite, plumstone and polystyrene, with median diameters in the range 500 to 1000 micron, and fall velocities from 22mm/s to 52 mm/s. The polystyrene, however, was the one material which fell outside these ranges, with a median diameter distribution lying between 400 and 600 micron, and with a fall velocity in the region of 5 mm/s. These values were considered in relation to the r.m.s values of turbulence measured in the clear water tests, where for the case of the current alone the r.m.s. values in the lower half of the boundary layer lay between 13 mm/s and 15 mm/s, and for waves and currents combined the comparable figures were 18mm/s to 25 mm/s. As a result of these tests the polystyrene particles were used in the study of sediment concentrations under waves and currents in the water tunnel.

Measurements of sediment concentration were achieved by aiming a low-power laser through the water tunnel onto a photodetector whose voltage output, related to the blockage caused by the sediment, was recorded by the on-line computer. The photosensor was mounted in a blackened tube and protected by band-pass optical filters to minimise the effects of extraneous light. It was necessary to use neutral density filters to control the initial power of the laser beam to avoid the saturation of the photodetector when no particles were present.

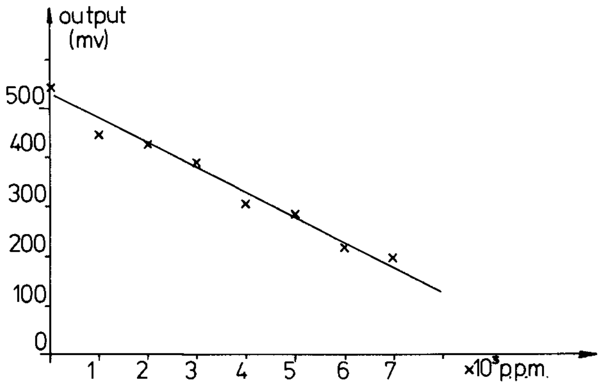

Fig. 1 Calibration curve for the laser sediment concentration meter using plumstone.

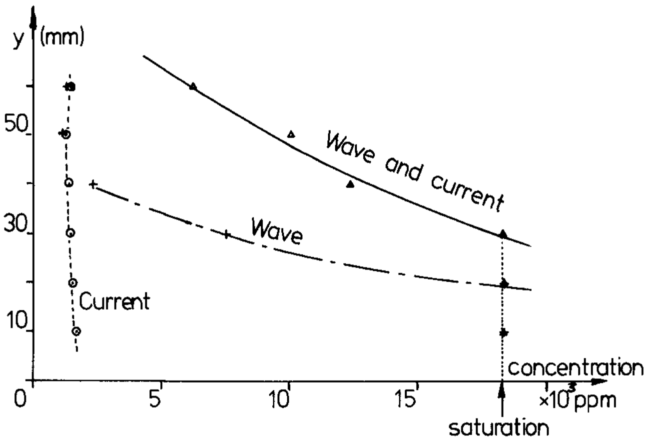

Fig. 2 Measurements of polystyrene concentration over a bed roughness apex, for combined wave and current, current alone and wave alone.

The system required calibration for the particular sediment in use, and this was done with the aid of a small perspex box of the same width as the water tunnel, placed between the laser and the photodetector. The box was filled with a mixture of glycerol and water, and a known volume of sediment added and shaken into suspension. The sediment was thus almost neutrally buoyant. For each concentration the box was oscillated across the beam, simulating the fluid motion anticipated in the tunnel, and the photodetector reading noted at regular intervals. The relationship between voltage and concentration was found to be closely linear for the plumstone (Figure 1), whereas for the polystyrene the curve was logarithmic. The glycerol mixture used maintained the sediment in suspension for long enough to give a reasonable sample length, while still allowing movement of the particles to produce an even distribution throughout the volume of the box.

RESULTS.

Waves and currents in the absence of sediment.

It was found that the unidirectional turbulent boundary layer is reduced in thickness by the superposition of waves propagating with the current over both rough and smooth beds. For all combined wave and current tests, flow reversal was experienced near the bed.

Waves propagating with the current over a rough boundary progressively reduce the mean velocities near the bed as the wave height is increased. For the smooth bed, however, waves with the current increase the velocity. Similar behaviour is experienced for waves on an opposing current.

In the outer flow the bed roughness effect becomes negligible. Here, for waves propagating with the current, mean velocities are reduced, whereas for the opposing current velocities are increased.

Figure 3 shows velocity profiles over a rough bed. The symbol WCR indicates waves and currents over a rough boundary. The mean centre-line velocity was 185mm/s. The wave heights in order were 22.7, 31.6, 40.4 and 46.6mm.

For the rough boundary tests the mean bed shear stress and roughness length scale were increased by the superposition of waves. Within two roughness heights of the rough bed the turbulence characteristics are dominated by the periodic formation of vortices. The overall increase in turbulence is limited to a region within six or seven roughness heights of the bed.

From these extensive initial tests and observations it was inferred that the combined stresses are likely to result in a considerable increase in sediment pick-up from a rippled bed.

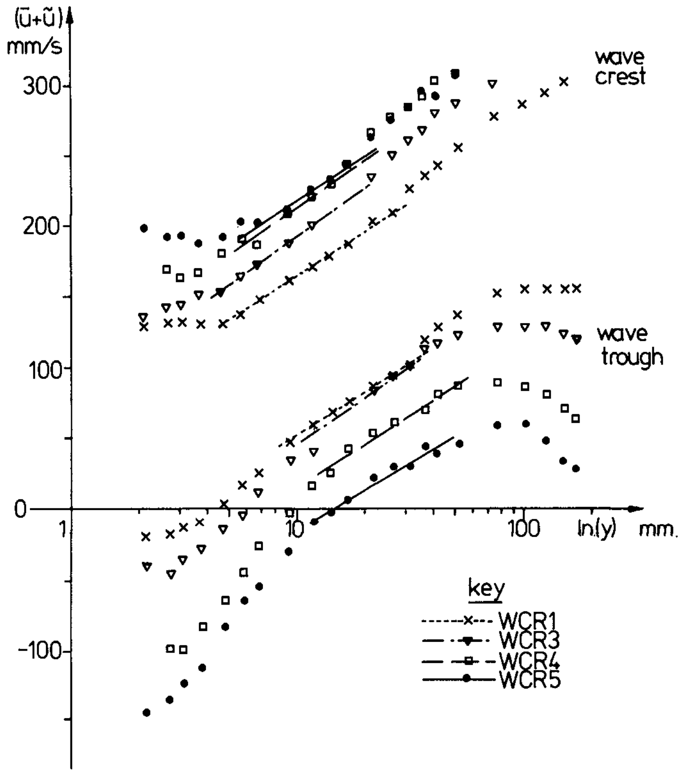

Fig. 3 Semi-logarithmic velocity profiles over a rough bed at phases corresponding to wave crest and wave trough; measured over the roughness apex.

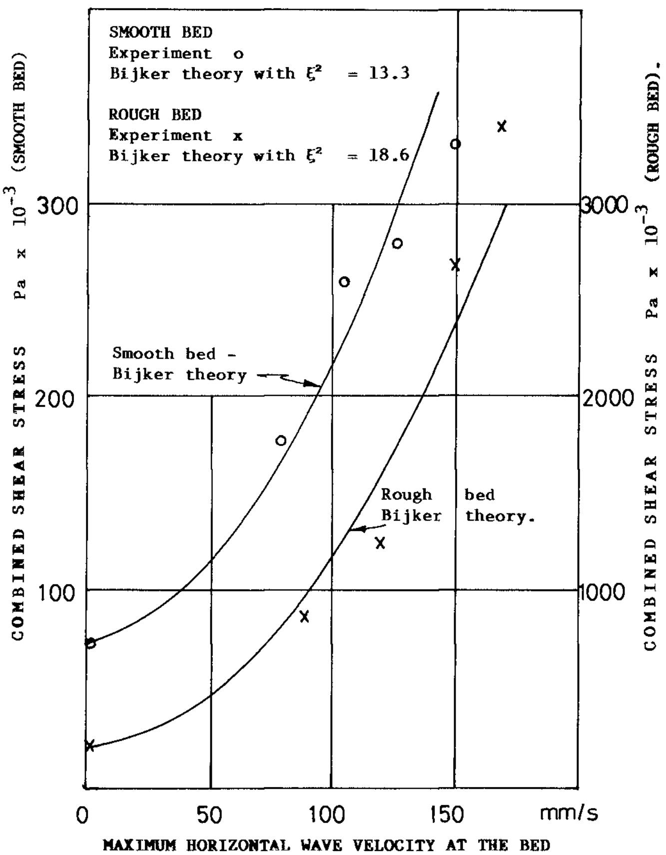

Fig. 4 Experimental values of combined wave & current shear stress, compared with the theory of Bijker (1980). See Appendix to this Paper.

Sediment response to the action of waves and currents.

Observations in both the standing wave rocking channel and in the small oscillating water tunnel showed that under the action of waves alone the sediment over the rough boundary, which consisted of triangular slats across the direction of motion, the sediment was put into suspension under the action of the vortices induced by the roughness elements. As predicted by the previous study in clear water reported above, the sediment layer was confined to a band only a few roughness heights in thickness. In the oscillating water tunnel the polystyrene particles under the action of the current alone produced only a very low concentration in the flow, and much of this consisted of the lighter particles which were maintained in suspension in the form of wash load. However, when this current was superimposed on the situation produced by the waves alone, the narrow band of vortex induced sediment in suspension rapidly expanded under the action of the turbulence. This is illustrated in Figure 2.

DISCUSSION AND CONCLUSIONS.

The main points arising from the clear water tests have already been set out under that heading above. However, from an experimental point of view and also in relation to the interpretation of the results and observations from other work in this area, the fact that the wave/current interaction reduces the boundary layer thickness both at the walls and the bed, means that the current is redistributed across the channel. All experiments of this nature should therefore take this into account.

So far as the sediment concentration is concerned when a current is superimposed on waves, it has been demonstrated that whereas the current alone might only produce slight movement of the bed particles, and the waves alone a dense concentration confined to a few roughness heights, the combination of the waves and currents produces a dramatic diffusion of the sediment layer.

Since the clear water tests provide data on shear stress under the action of waves and currents for both smooth and rough boundaries, it is of interest to substitute these in the expression proposed by Bijker (1980). This has been done in Figure 4 and the parameter ξ derived from these curves is shown on the diagram for the two cases.

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APPENDIX. Comparison of experimental values of combined wave and current shear stress with the theory of Bijker (1980)

According to Bijker : $V_{*cw} = V_{*c}\{1 + \frac{1}{2}(\xi\tilde{u}_o/\overline{V})^2\}^{\frac{1}{2}}$

which can be written : $\tau_{cw} = \tau_c\{1 + \frac{1}{2}\xi^2\tilde{u}_o^2/\overline{V}^2\}$

The experimental results of Kemp & Simons in the present Paper have been used to evaluate the shear stresses as follows:-

SMOOTH BED: $\tau_{cw} = \{\nu.\frac{d}{dy}(\overline{u} + \tilde{u}_{max})\}_{bed}$

ROUGH BED : $\tau_{cw} = \{\rho(\widetilde{u'v'})_{max} + \tilde{u}_{max}\tilde{v}_{max}\}$

where τ_{cw} = wave + current shear stress; τ_c = current alone shear stress; ξ = wave and bed roughness factor; $\tilde{u}_o$ = max. orbital velocity at the bed; $\overline{V}$ = mean current velocity; ν = kinematic viscosity; $\overline{u}$ = local mean current velocity; $\tilde{u}_{max}$ = local orbital velocity; $\tilde{u}'$ and $\tilde{v}'$ = horizontal & vertical turbulent velocities.