SEDIMENT TRANSPORT DUE TO WAVES AND TIDAL CURRENTS

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Introduction

One of the long established maxims of the coastal engineer is that "waves disturb, currents transport". In spite of considerable study and research, there is still some way to go before the physics of this process is understood and can be expressed in quantitative terms. In fact, the constituent elements of waves, currents and sedimentation, each contain large areas of uncertainty. However, it is accepted that waves may entrain significant amounts of sediment when a current of comparable magnitude may be too weak to initiate sediment motion.

Advances in this area are being made on two fronts. Firstly empirical and semi-empirical methods are being developed which can help to provide answers to practical problems in the short term. At the same time the study of the physics of the problem is being pursued, which in the longer term will provide a more sure foundation on which to base sediment transport calculations.

The systematic study of the physics of this area may be illustrated by some of the relevant research topics on which the authors and their colleagues have been engaged over the past two decades. These include the study of boundary layer turbulence Grass (1971), the initial movement of fine sand Grass (1970), the initiation and propagation of sand ripples Williams & Kemp (1971) (1972), flow in the separation zone downstream of ripples Etheridge & Kemp (1978)(1979), field studies of turbulence and sediment transport Russell (1976) and Russell & Kemp (1977), the interaction between waves and currents Kemp & Simons (1982) (1983), and the vortex structure in turbulent boundary layers Grass (1983). Parallel work in other institutions and countries is at the same time building up the overall picture.

The complex nature of loose boundary hydraulics is related to the continual interaction between the fluid and the sediment, and hence of the bed geometry. Even in purely tidal situations in the absence of waves, the ability to predict siltation to within a factor of two is considered reasonable Thorn (1981). When waves are superimposed on currents it is clear from field observations that the increase in sediment transport is dramatic. Owen and Thorn (1978a) (1978b) in a nearshore field study compared the suspended sediment transport for tidal currents alone with measurements made during periods of wave action, and found that the waves increased the transport by up to forty times the current-only case. Kana & Ward (1980) similarly found increases of sediment load of ten times, and an increase in sediment transport of sixty times, when the increase in extent of the active zone and the greater height to which the sand was suspended were taken into account. The urgent need for an improved understanding of the flow in the boundary layer under wave and current action is thus clearly recognized. The present paper will report on the authors' recent work in this field.

Brief review of the main factors

The shear stress at the bed is one of the dominant factors in all sediment transport calculations. The mean shear stress is most commonly used, although as Grass(1970) has demonstrated for unidirectional flow, there is both a distribution of shear stress on the bed, and a distribution of shear stress value at which the sediment will move. Etheridge & Kemp (1979) have pointed out that bed material can move under conditions of zero mean shear stress, notably at the reattachment area downstream of steps or ripples where very large positive and negative values of instantaneous stress occur. In addition the large scale turbulence structures known as ejections and sweeps, associated with the bursting process, account for the major contribution to the Reynolds stress. The process is described by Kline et al (1967), Corino (1969), Grass (1971), Jackson (1976) and others.

A recent description of the flow structure of the turbulent boundary layer is given by Grass (1982). Bursting has been measured in the field by Russell (1976),Russell & Kemp (1977), Soulsby et al (1983), and can move sediment up through the whole of the boundary layer as described by Jackson (1976) and Fukuoka & Fukushima (1980). Together with Itakura & Kishi (1980) they have noted an association of bursts with large bed features. Madsen & Grant (1975) in a discussion of a paper by Komar & Miller (1973) show that Shields shear stress parameter (see Graf 1971; Raudkivi 1976) can equally well be applied to oscillatory conditions. Similar shear stress expressions appear in a variety of sediment transport equations.

The many sediment transport equations mentioned above have been reviewed and compared by various authors. White et al (1975) compared eight theories relating to unidirectional flow on the basis of 1000 flume and 260 field measurements. For the better theories the predicted transport rates were between 0.25 and 4 times the observed rates for about 85% of the data. Ackers & White (1980) made a further review when proposing a new theory. Graaff & Overeem (1979) compare formulae on the basis of their overall trends and sensitivity to changes in the value of the parameters. They point out that these formulae have been adapted and not designed for coastal conditions, and they do not see any significant advances in this area until the general physics is better understood.

Bed friction is related to the nature of the bed material and to the geometry of the bed. Mention will be made of bed forms later in the paper. It must be remembered that so far as the bed material is concerned, this is not always non-cohesive. Mantz (1980) points out that grain surface interaction effects begin to affect silica grains for median diameters less than 100μm. Different effects are produced in pure water, sea water and soft water. Whereas sea water and hard water increase cohesion, pure water induces repulsion, and soft water makes them cohesionless. The latter effect was exploited by Mantz in his experiments.

In addition mud has a differential response to bed shear stress, depending on the depth of erosion, see Thorn (1981) and Miles (1981).

Bed roughness can include grain roughness, ripple roughness and a component associated with the movement or suspension of the bed material. When ripples are present their influence on sediment transport will depend on whether or not separation occurs. Separation may not occur if the ripples were formed under earlier wave conditions , Soulsby et al (1983). The occurrence of bed forms can be related to a modified Shields parameter, as discussed by Sleath (1978), and in the form proposed by Brebner (1980). Brebner states that bed forms do not occur until $\Psi > 3$. Ψ is given by $\Psi = (a\,\omega)^2/(s-1)gD$, where a = wave orbital amplitude at the bed, ω is the orbital angular velocity, s = relative density, and D the grain diameter. Brebner mentions that bed forms may be initiated by small irregularities. Williams & Kemp (1971) (1972) define similar conditions for ripples which form in unidirectional flow. The ripple steepness η/λ depends on the shear stress. Here η is the ripple height, and λ the ripple wave length. There is general agreement that ripple steepness lies in the range 0.13 to 0.22 for values of Shields parameter θ' less than 0.4, where θ' is given by $\theta' = \frac{1}{2}(a\omega)^2 f_w/[(s-1)gD]$ as quoted by Nielsen (1981).The friction factor f_w is based on Jonsson (1965) (1966) or Swart (1974). For $\theta' > 0.4$ ripples start to flatten out, and for $\theta' > 1$ the bed is virtually plane. Values of η/λ in the above range have been reported by Bagnold (1946), Brebner (1980) Miller & Komar (1980), Nielsen (1981) and Soulsby et al (1983). Similarly under moderate conditions when $\Psi < 20$, the ratio of ripple length to orbital diameter at the bed is approximately constant at a value of 1.3, although with lightweight materials this may go up to 2. Grant & Madsen give an alternative criterion for the breakdown of ripples to that quoted above by Nielsen. Grant & Madsen suggest that breakdown occurs if Shields' parameter is exceeded by a factor $1.8\ S_*^{0.6}$ where $S_* = \frac{1}{4}D/\nu\ [(s-1)gD]^{\frac{1}{2}}$, where ν is the kinematic viscosity of water. Their expression is seen to be equivalent to 32 $D^{1.5}$ for quartz grains. Further reference may be made to Grant & Madsen (1982).

The effect of asymmetrical ripples on the direction of sediment transport was studied by Inman & Tunstall (1972), Inman & Bowen (1962) and Bijker et al (1976). Inman & Tunstall found that for $\eta/\lambda < 0.2$ sediment moved in a direction from the steep to the flatter face of the ripple. This was observed both in the laboratory and in the field. Vortex asymmetry is also discussed by the present authors in relation to wave and current interaction, and by Sleath (1982) in regard to sand suspension by waves.

Ikeda (1980) comments on a ten -fold increase in sediment transport when ripples change from two to three dimensional shape, although the mean shear stress remained almost constant. The change was associated with turbulent bursts and spiral flow. It has been observed that in unidirectional flow,sand movement can reduce the velocity near the bed to a near uniform value; see Iwasaki & Hanzawa (1980).

The combination of waves and currents is frequently met in tidal channels. Even in the absence of waves the situation is complicated. The flow is frequently unsteady, non-uniform and spatially variable, although for certain phases of the tide the flow may be quasi-steady. In addition a wide range of sediments may be present, although some areas of the bed may consist of inerodible material. In this situation mathematical models are no better than the extent to which the simplified assumptions happen to fit the particular circumstances. Empirical coefficients relating to sediment movement must be determined for each site studied, calculations being based on a prediction of the changes in water movement. If it is assumed that the flow is reasonably steady, the material is fairly coarse and closely graded, and that the sediment load represents saturated conditions, a simple potential load model can be used which is based on the equation :

$\frac{\partial m}{\partial t} + \frac{\partial}{\partial x} . (T_s) = 0$ where T_s must be provided from a sediment transport equation. However, the conditions which prevail may include unsaturated flow, differences in turbulence between accelerating and decelerating phases, unsteady non-uniform currents, and the assumption of an eddy diffusivity. However, for unsteady and uniform conditions the basic equation would become

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z} (\varepsilon \frac{\partial C}{\partial z}) + w_s \frac{\partial C}{\partial z}$$

where ε is the coefficient of diffusivity, C is the concentration, and w_s is the fall velocity of the sediment particles.

The diffusion coefficient, the Reynolds stress and the kinetic energy are larger in decelerating flow than in accelerating flow. Russell & Kemp (1977), and Anwar & Atkins (1980). Field measurements by Soulsby & Dyer (1981) suggest that during accelerating flow the sediment is responding to turbulence produced at an earlier point in time. Also in tidal flow the fall velocity of the particles causes a time lag of suspended solids concentration with respect to the depth-mean water velocity, as shown by Thorn (1981). Close to the bed Thorn found that the concentration was given by $C_o = E.u_*^p$ where E is a coefficient, u_* is the shear velocity, and p increases with particle size, being about 6 for fine sand. Sediment stratification can also modify the flow. Soulsby et al (1983) develop a theoretical expression describing the conditions for sediment stratification to exist, and the degree of stratification. A useful review of the problems of modelling sedimentation in tidal channels has been given by Miles (1981).

Sediment transport due to waves and currents.

Methods which are currently used for calculating sediment transport for combined wave and current conditions can be used to identify areas where uncertainties exist and research is required.

Broadly speaking it is necessary to define the combined shear stress at the bed. This must be derived from assumptions or measurements of the separate wave and current induced velocities, and their resultant value. This involves a choice of wave theory and an assumption of say a logarithmic current velocity profile. Implicit in these definitions is an assessment of a bed roughness or friction factor. The formulation must then define a diffusion coefficient which can be used in conjunction with a separately determined value of sediment concentration in the bed layer, to give a sediment concentration distribution with height. Based on the assumed current velocity distribution, the total sediment transport can then be obtained by integration over the depth. There are variations on this approach but it is presented in order to highlight the uncertainties involved.

The general approach outlined above may be illustrated by reference to the equation developed by Bijker (1967, 1971, 1980).Central to his method is the computation of the total bed shear stress τ_r in terms of the shear stress τ_c due to the current alone, in the form

$$\frac{\tau_r}{\tau_c} = (1 + \tfrac{1}{2} \xi^2 \frac{U_o^2}{V^2})$$

where U_o is the amplitude of the orbital velocity at the bed, and V is the mean current velocity. The coefficient ξ can be evaluated from the friction factors of Jonsson (1965, 1966) or Swart (1974), expressed as f_w, from which $\xi = C_h (f_w/2g)^{\frac{1}{2}}$ where C_h is the Chezy coefficient. The friction coefficient based on Swart's formula is $f_w = \exp[5.213(k/a)^{0.194}-5.977]$ and k = the roughness value. The sediment concentration at a height z is then $C = C_o \exp(-w\, z/\varepsilon)$.

Bijker (1971) adapts a sediment transport formula due to Frijlink for unidirectional flow viz. $S_b = 5\, D_{50} (\frac{\mu\ \tau}{\rho})^{\frac{1}{2}} \exp(-0.27\, \Delta\, D. \frac{\rho g}{\mu \tau})$

where D = grain diameter, μ = a ripple coefficient, Δ = the relative density of the bed material . By substituting τ_r for τ, and after expressing τ_c as $g \frac{V^2}{C_h^2}$ he obtains

$$S_b = 5\, D\, V \frac{g}{C_h}^{\frac{1}{2}} \exp[-0.27\, \Delta\, D\, C_h^2/\{\mu.\ V^2 [1+\tfrac{1}{2}(\xi \frac{U_o}{V})^2]\}$$

Mikklesen et al (1980) propose a sedimentation model which determines the wave boundary layer thickness from Jonssen & Carlsen (1976). They add the wave and current velocities just outside the boundary layer, and use f_w to find the shear stress from $\theta' = \frac{1}{2} f_w \frac{U}{(s-1)gD}$

Rasmussen & Fredsøe (1981) tackle the problem of currents acting at right angles to the direction of wave propagation, on the basis of laboratory experiments using 180µm sand. Their velocity relationships are based on Fredsøe (1981) which assumes that the wave boundary layer dominates the inner region whilst the turbulence in the outer region is generated by the current. They assume a logarithmic velocity profile and an enhanced wave-induced roughness. Eddy viscosities for waves and currents are added at the bed so that $\varepsilon_{cw} = (U_{*w} + U_{*c}).z$

The velocity profile in their inner solution where $U = 0$ at $z = k/30$ is

$$\frac{U}{U_{*c}} = \frac{2.5\ U_{*c}}{(U_{*c} + U_{*w})} \ln(\frac{30z}{k})$$

For the outer solution $\frac{U}{U_*} = 8.6 + 2.5 \ln(z/k)$ where k is derived from Jonsson. They report reasonable agreement between experiment and theory.

Vincent & Young (1982) use the wave and current interaction theory of Grant & Madsen (1978) (1979) which uses an apparent roughness in the log. velocity formula, and collate this with a sediment concentration observed as $C_z = C_1(1 - A \ln.z/z_1)$ where $A = 0.22$, and C_1 is the concentration at the height z_1, where z_1 is taken as 1cm. Jonsson's friction factor is again implicit in their formulations. They emphasize the uncertainty in the eddy viscosity and in the value of the measured roughness parameter which varied from 10µm to 250mm. which is equivalent to physical roughness values of up to several metres.

Willis (1978) used the Ackers & White (1973) formula and a transport power approach where the power $P = \tau V$, together with Bijker's shear stress formulation translated into the form $\tau = \rho \left(\frac{V^2}{C_h^2} + W^2 \frac{f_w}{4} \cdot U_o^2\right)$ where W = an empirical coefficient. His sediment transport power equation then becomes $P = \rho \left[\frac{V^2}{C_h^2} + W^2 C_g f_w/4 . U_o^2\right]$ where C_g = wave group velocity. Willis used twentyseven measurements of sediment load to evaluate the Ackers & White parameters and his coefficient W.

The authors of all these sediment transport formulations conclude that there is a need for more information from experimentation.

Wave and current interaction

The prediction of sediment motion relies on a knowledge of the fluid motion. Clearly it is of interest to know whether a logarithmic velocity profile persists when waves are superimposed on a current. In addition the conditions under which flow reversal occurs near the bed, and the extent to which wave motion may modify the current-induced turbulence in the boundary layer are important in relation to sediment motion. Interest also centres around the predicted increase in apparent roughness under the combined fluid motion. The research programme pursued by the authors was designed to look 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 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.

Comparatively little previous work had been carried out on the interaction between waves and currents, particularly near the bed. Grant and 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 were superimposed on the current. A similar theory has been presented by Christoffersen (1980). Bakker & van Doorn (1979) also found an apparent increase in 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 in more detail may be found in Kemp & Simons (1982, 1983).

Experimental investigation of wave/current interaction

The apparatus used by the authors in their investigation is described in Kemp & Simons (1982).The work was carried out in an open channel using monochromatic waves. Two bed conditions were used as mentioned above. With the smooth bed the current alone was well into the turbulent regime, whereas the waves alone were laminar. With the two dimensional roughness elements the current was fully rough turbulent. The larger waves by Jonsson's criterion were at the top of the transitional range, but it was felt that the sharp-crested triangular elements would induce earlier transition to turbulence than he predicted. Spectrum analysis was carried out on the waves, and this eliminated any suggestion that any of the effects observed might have been due to the presence of parasitic waves resulting from imperfect wave generation. The height and spacing of the roughness 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 the turbulent and wave-induced velocities was carried out using an on-line 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.

The flow depth was kept constant at 200mm, and one overall flow rate was used throughout each test. For currents flowing with the waves the mean centreline velocity was 184mm.s^{-1} . For waves opposing the current the equivalent velocity was 111mm.s^{-1} . Four different wave heights were used with a wave period of 1 second.

When scaled on suitable flow parameters, a logarithmic mean velocity profile was found for the currents alone, following the universal law of the wall for both rough and smooth boundaries, with von Karman's constants of 0.36 and 0.4 respectively. Turbulent intensities and Reynolds stress measurements in the wall layer were in good agreement with previous research (Laufer 1950), Grass 1971).

For the waves, the range of a_{bm}/k_s lay between 0.46 and 0.85, where a_{bm} = orbital amplitude of a particle at the outer edge of the wave boundary layer, and k_s is the Nikuradse equivalent sand roughness. Wave surface profiles and wave-induced periodic velocities corresponded very closely with Stokes' second-order theory and with Brink-Kjer & Jonsson's theory (1975).

The test programme included measurement of wave height attenuation along the channel, and determination of the rough boundary friction factor

f_w. The wave attenuation was found to be greatly increased by the addition of an opposing current, and reduced by a following current. The wave friction factors were determined from Kamphuis (1978) and compared with those derived from Jonsson & Carlsen (1976) and Kajiura (1968). The experimental results lay between those predicted by these two theories.

Combined waves and currents - waves travelling with the current.

The results from tests over both rough and smooth beds show a marked reduction in maxima and minima of the periodic wave-induced velocity near the bed.

Over the smooth bed the effect of introducing a wave was to increase the mean current velocity near the bed. With a rough bed there is a reduction in mean velocity within two roughness heights of the apex level, with increasing wave height. The results show that a linear superposition of the separate wave and current velocities does not hold.

Most of the current sediment transport theories for the combined wave and current situation have assumed that the mean velocity profile remains logarithmic after the waves have been superimposed. The authors' results as depicted in Figure 1 confirm this. In the case of the rough boundary however, the mean shear stress deduced from the slope of the logarithmic profile is significantly higher than that for the current alone. Figure 2 also shows that the roughness length scale z_o (the intercept of the log line with $\overline{u} = 0$) increases with wave height up to two times the current only value.

Measurements over the trough of the bed roughness show that there is an increase in return (against the current) flow between the elements, over that measured with the current alone. The duration of this return flow increases with wave height H, thus allowing the formation of 'upstream' vortices, which induce downstream velocities in the roughness troughs. It is of interest to note that flow reversal takes place near the smooth bed for all the waves tested. Over the rough bed the reversal layer is thicker varying between 3mm and 15mm above apex level.

From the velocity profiles close to the smooth bed it is possible to calculate the maximum and minimum bed shear stresses τ_{max} and τ_{min} induced periodically by the waves and currents. The maximum bed shear velocity is approximately double the mean over the wave cycle estimate for the larger waves.It is also apparent that the large periodic variations in $\tilde{u}_*$ close to the bed are not transmitted out into the logarithmic region, although the value of $\tilde{u}_*$ was found to vary from $\bar{u}_*$ in this layer by 20% in the larger waves and 10% in the smaller ones. This indicates a wave-induced turbulence not found in tests on waves alone.

The turbulence characteristics for the smooth boundary indicate that the horizontal turbulence component varies through the wave cycle. Close to the bed where wave action induces flow reversal, there are peaks in r.m.s at the phases of zero velocity, the larger disturbances occurring during the deceleration phase. Further from the bed the combined flow intensities fall below the values for current alone. This bears out the results of the mean velocity profiles, that the addition of waves reduces the thickness of the boundary layer. For this smooth bed case it appears that there is no significant increase in turbulence intensity caused by the addition of the wave.

In the case of the rough boundary the turbulence intensity fluctuates considerably in both directions through the wave cycle, particularly within two roughness heights above the bed apex, a layer 10mm thick. Here there is a maximum intensity at a phase corresponding to maximum deceleration, with a small peak during the accelerating phase. The superposition of even the smallest wave tested causes a dramatic increase in turbulence over the values for current flow alone. Figure 3 emphasizes the way in which the intensities increase with wave height, illustrated with respect to the vertical component. Figure 4 reveals that the rate of increase with wave height of turbulence intensities near the boundary is reduced by the addition of the current.

Figure 5 shows the eddy viscosity distribution over a rough bed plotted against the height above the bed. The figure suggests that the assumption of Grant & Madsen (1979) that there is a boundary layer of two regions with a linearly varying eddy viscosity in each is reasonable for most of the outer layer, although in the wave layer near the bed the distribution is scattered, and suggests a constant value of eddy viscosity.

Waves travelling against the current.

The periodic velocities outside the rough bed boundary layer, of about two roughness heights, and up to the surface were in good agreement (within 2%) with the theory of Brink-Kjaer & Jonsson (1975) for second order waves on a linear shear current. Velocities predicted by neglecting the current and simply applying second order wave theory to the measured wavelength and height would underestimate results by 15%.

Within the layer two roughness heights above the rough bed apex level periodic velocities were greater than the profile predicted near the bed. Values increased to a maximum at the bed apex level, where velocities 50% in excess of theory were measured. This behaviour was induced by vortices shed from the rough bed, and was similar to that experienced in the tests on waves alone.

So far as mean velocities are concerned over smooth and rough boundaries the effect of superimposing waves of increasing height onto a current propagating against the waves is to increase the mean velocity in the upper flow. This is the opposite effect to that found for waves on the following current. Near the rough boundary, the results showed the same behaviour as for the waves on the following current. The superposition of waves of increasing height led to a progressive decrease in mean velocity above the roughness apex level, with the reduction extending up through the logarithmic layer. In the roughness troughs, the mean flow against the current increased with wave height.

In this case too, it was found that the logarithmic layer persists after the waves have been imposed. The changes induced in the region are independent of direction relative to the wave. Over the rough bed the mean bed shear stress and roughness scale deduced from the slope and intercept of the logarithmic curve both showed an overall trend to increase with increasing wave height. For the largest waves tested, shear stress increased by a factor of three, and roughness scale by a factor of six times the values for current alone.

The distribution of eddy viscosity with depth was computed from the mean bed shear stress and mean velocity profile, using the relationship

$$\varepsilon = \frac{\bar{\tau}_b}{\rho d\bar{u}/dz}$$

as assumed in Christoffersen (1980). The results in the turbulent boundary layer indicate a linear distribution in all cases, with the slope $d\varepsilon/dz$ increasing with wave height. Near the rough bed a linear distribution of different slope was found, for both the current alone and for the current with the smaller waves, but as the wave height increased, so the results became more scattered.

Turbulence intensities in the smooth bed case showed the same periodicity as in the previous case.

Near the rough boundary, considerable disturbance was introduced into the flow by the vortices formed in the roughness troughs. Within 5mm of the bed there were two peaks of turbulence activity corresponding to phases of acceleration and deceleration, the deceleration effect being greater. As the current was flowing against the direction of wave propagation, this occurred as the wave crest was approaching and the water level rising. In the experiments already described when the current was in the direction of wave travel and in which a stronger current velocity was present, there was only one peak near the bed, and that too corresponded to the decelerating phase, in that case after the wave crest had passed.

The variations in Reynolds stress through the wave cycle for the rough bed confirmed the results of the horizontal turbulence. At the phase prior to the passage of the wave crest there was a sharp reversal in Reynolds stress to a value ten times the mean value for current alone. At the phase corresponding to a maximum acceleration there was a relatively mild peak, though with a positive value five times that for current alone.

For the rough boundary the turbulent boundary layer is far thicker with the combined flow, and of two to three times the intensity of the current alone.

Discussion and conclusions.

Much of the discussion is included in the text, and only some of the more general points are summarized here.

Changes in wave attenuation rate were different for the currents of opposite directions, indicating a direct interaction effect.

The logarithmic description of the mean velocity profile was found to be valid for waves in both directions, and throughout the wave cycle. However, longer shallow water waves might influence the logarithmic layer.

Near the rough bed mean velocities are increased in magnitude by the presence of waves in both cases.

Variations in turbulence intensity during a wave cycle near the rough bed were different for the two tests. This was due to the different magnitudes of the current velocities relative to the wave velocities. For the weaker opposing current, flow reversal against the current took place every cycle, causing the generation and ejection of an upstream vortex in addition to the usual downstream vortex. This behaviour was similar to that for waves alone. With the stronger following current, the upstream vortex was far weaker, if formed at all, leading to the formation and weaker ejection of only one vortex each wave cycle.

The presence of wave-induced vortices in the layer above the rough bed causes a drop in mean velocity, and a large increase in apparent bed roughness and shear stress as determined from the mean velocity profiles. This was found for waves propagating both with and against the current, and is as predicted by the theories of both Grant & Madsen (1979) and Christoffersen (1980). The measured values appear to be in better agreement with the latter.

Turbulence intensities averaged over the wave cycle are increased by the presence of waves irrespective of current direction, the increase being within two roughness heights of the bed.

For all combined wave and current tests, including smooth and rough beds, flow reversal was experienced near the bed.

Possible implications in relation to sediment transport.

The results of the research outlined above should enable some of the existing assumptions such as that of the logarithmic velocity distribution, the thickness of the apparent roughness and the eddy diffusivity, to be used with added confidence in sediment transport theory. The results concerning flow reversal at the bed confirm and extend the understanding of the circumstances and reasons for this effect. The increases in shear stress and turbulence may also help to explain or interpret observations of sediment motion.

The entrainment of material from the bed can be considered to show a significant increase under the combined action of waves and currents, but the distribution of turbulence intensities suggests that the zone of diffusion would not increase unless the sediment were further diffused under the action of spilling breakers or of the turbulence in the current.

Continuing research.

Separate experiments are currently being 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 are borne out by comparable changes in the distribution of the sediment in suspension. Preliminary results are shown in Figure 6.

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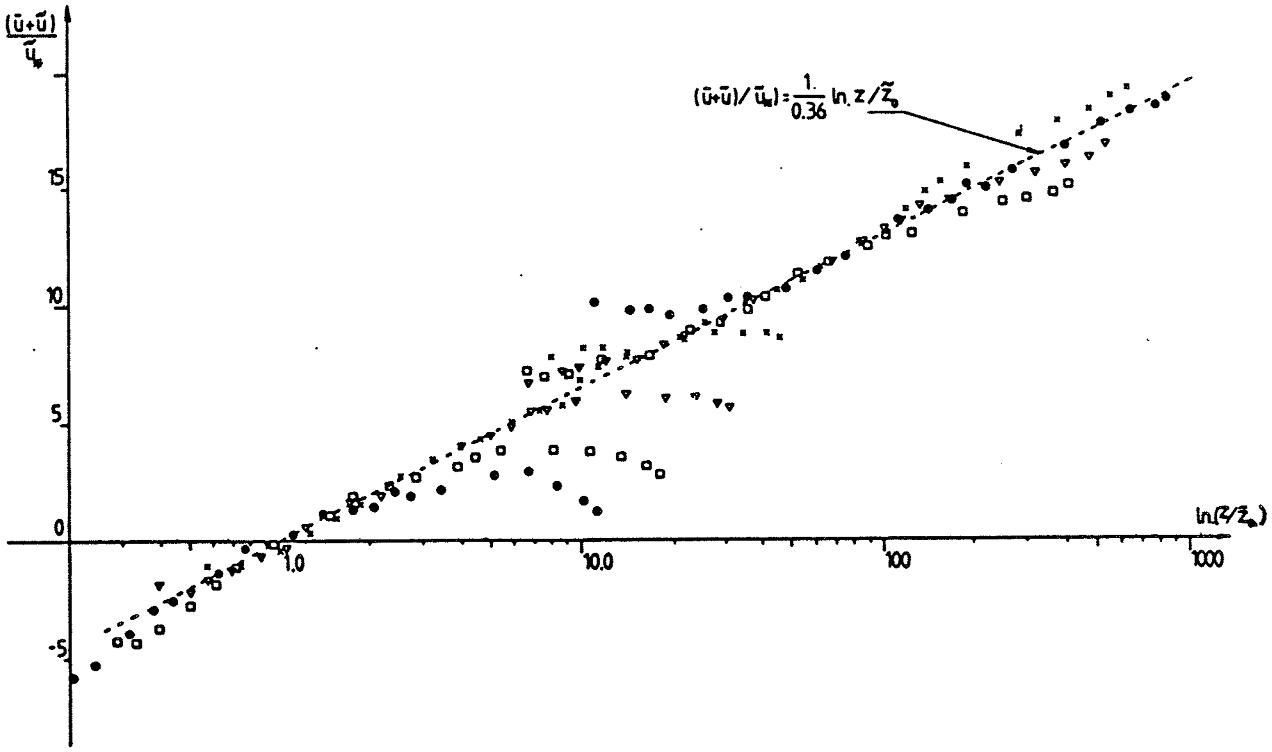

FIGURE 1. Normalised semi-logarithmic velocity profiles measured over a rough-bed apex, at phases corresponding to wave crest and trough.

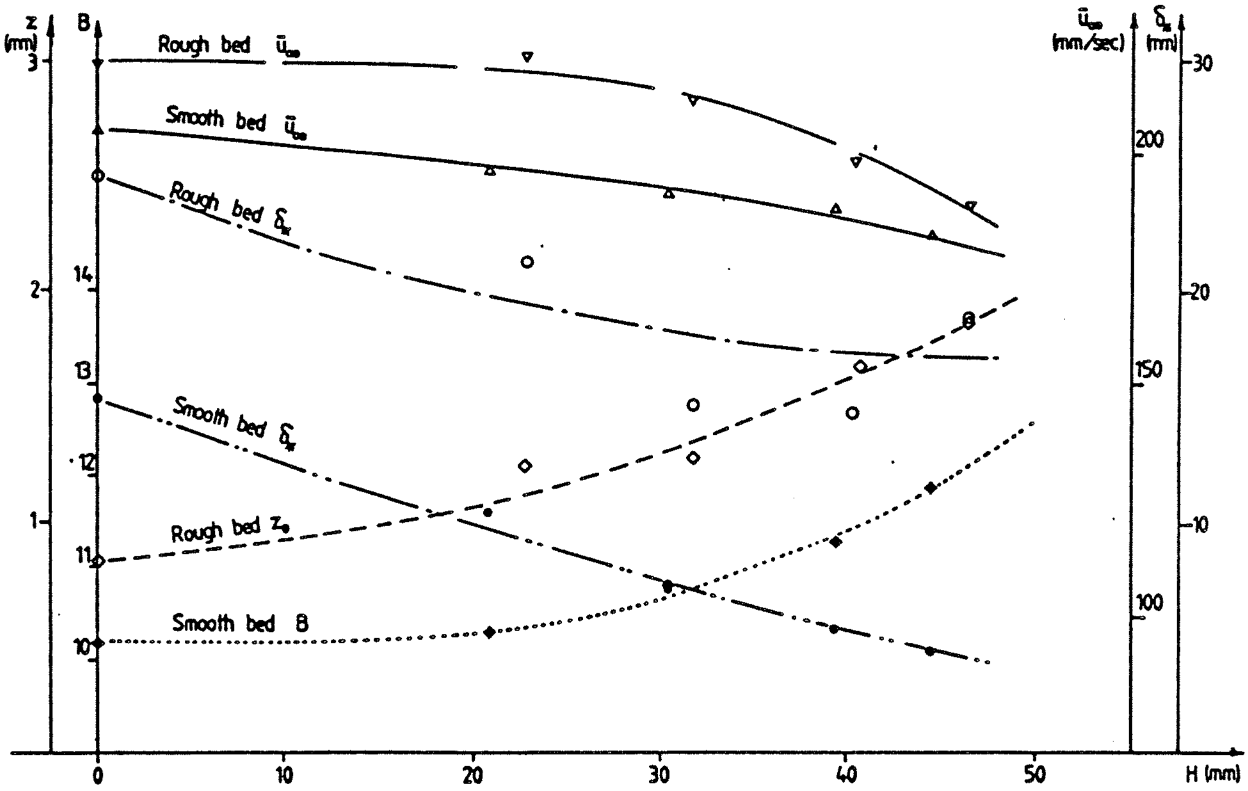

FIGURE 2. Variations in boundary-layer parameters and $\bar{u}_\infty$ with wave height.

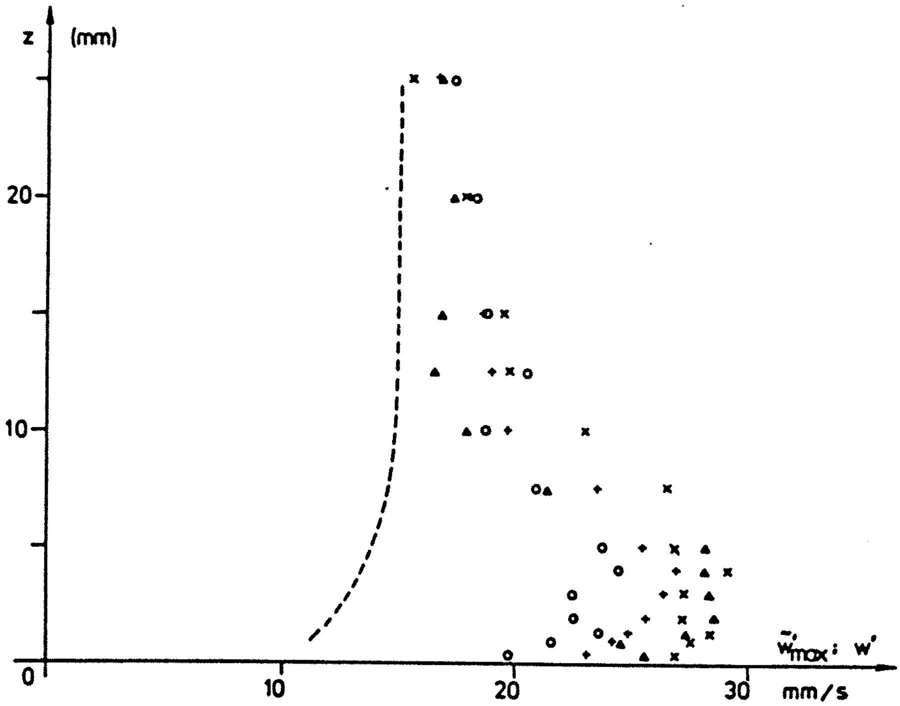

FIGURE 3. w';$\tilde{w}'_{max}$ vs. z within 25mm. of bed roughness apex. Current alone; w' ------. Wave + current; $\tilde{w}'_{max}$, O, WCR1; +, WCR3; x, WCR4; Δ, WCR5.

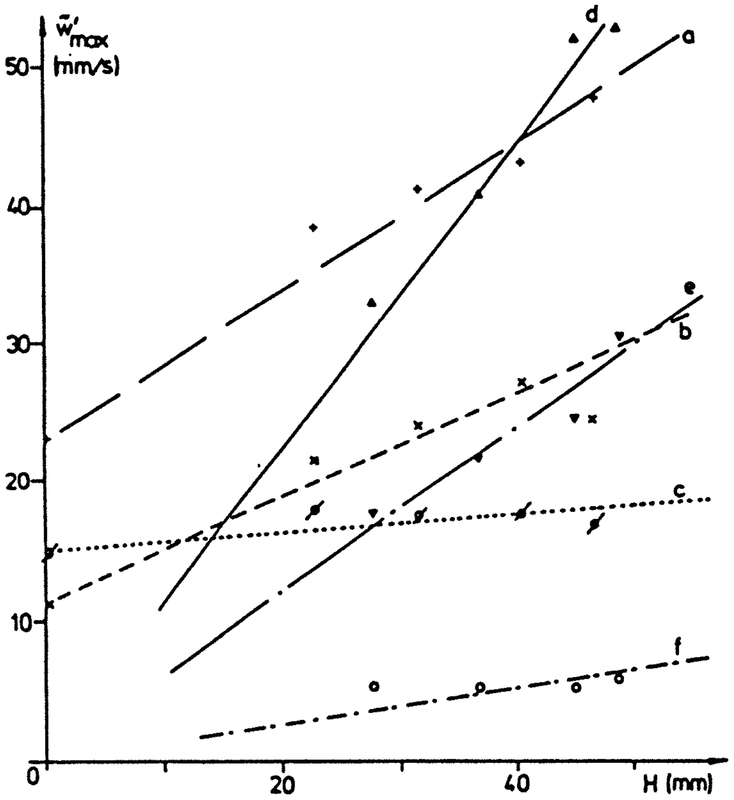

FIGURE 4. Increase in $\tilde{w}'_{max}$ with wave height.
Wave + current: (a) 5mm. above trough;
(b) 1mm. above apex; (c) 20mm above apex.
Wave alone: (d) 5mm. above trough; (e) 1mm. above apex; (f) 20mm. above apex.

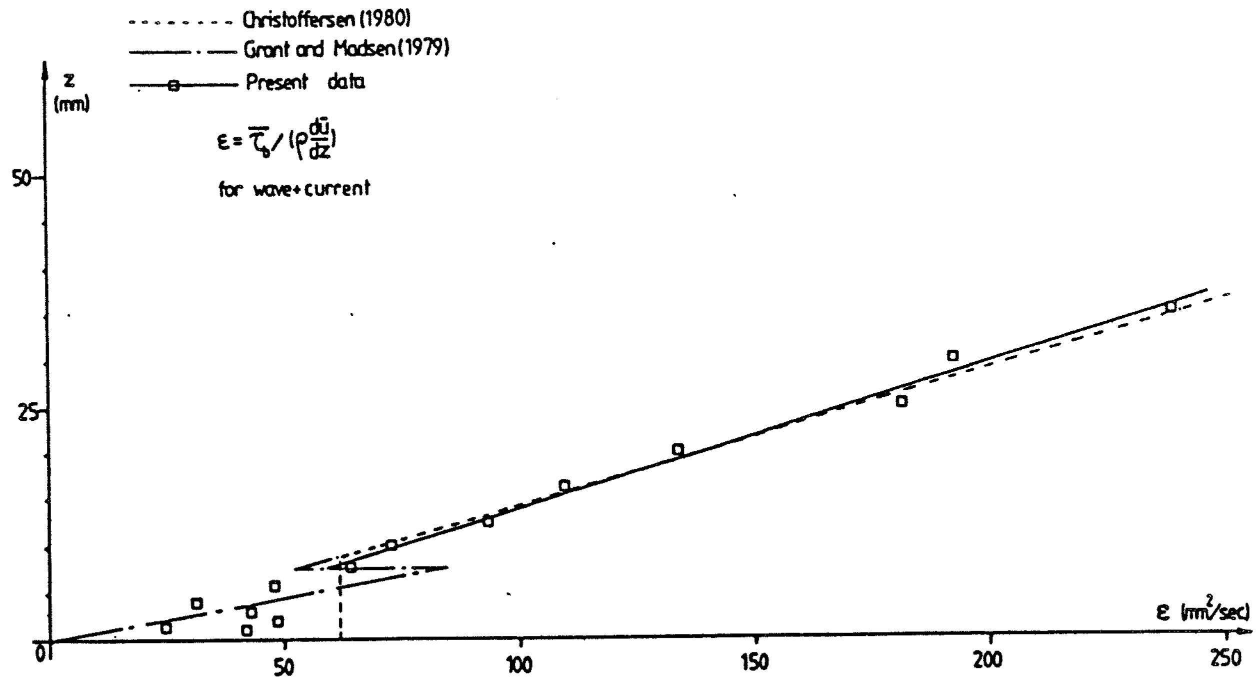

FIGURE 5. Eddy-viscosity distribution over rough bed: run WCR3. – – –, Christoffersen (1980); —— - ——, Grant & Madsen (1979); ———, present data. $\varepsilon = \bar{\tau}_b(\rho d\bar{u}/dy)^{-1}$ for wave and current.

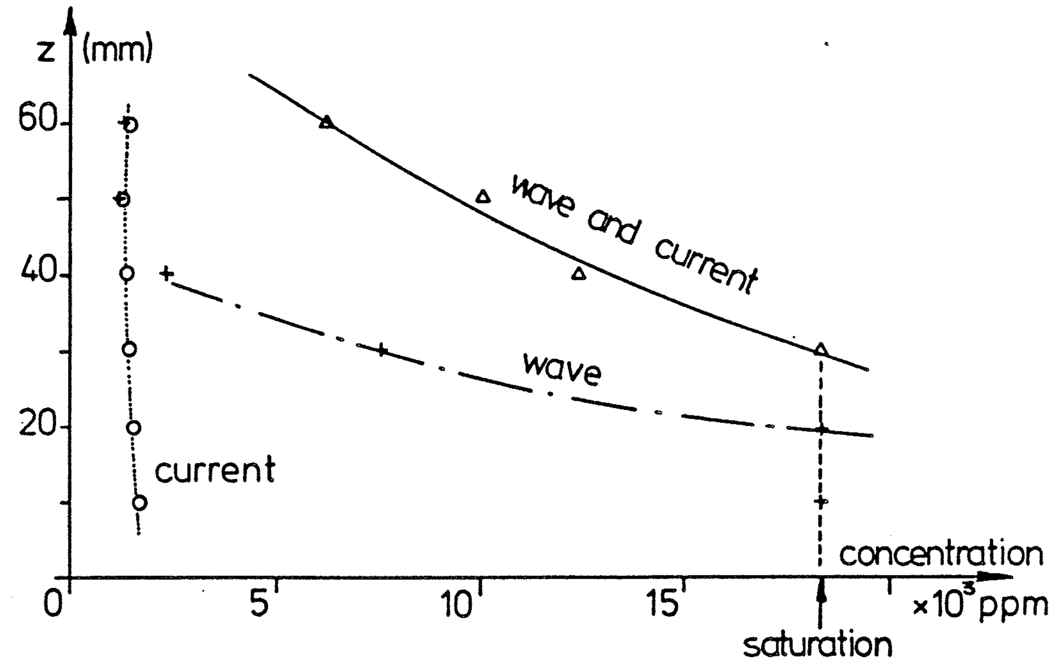

FIGURE 6. Measurements of polystyrene concentration over a bed roughness apex, for combined wave and current, wave alone, and current alone.