CHAPTER 195

COMBINED FLOW SAND TRANSPORT: FIELD MEASUREMENTS

RICHARD J.S. WHITEHOUSE[1]

ABSTRACT

This paper compares the results of measurements obtained from two field experiments performed to determine the effect of waves and currents (w+c) on the transport of sand in suspension. One set of measurements are from an estuary (Maplin Sands) and the other are from the surf zone (Boscombe Pier). The vertical and temporal variation in and the correlation between some of the hydrodynamic and sediment dynamic parameters are discussed.

1. INTRODUCTION

The ability to predict the transport rate of sandy sediment by combined wave plus current (w+c) action is an important aspect of many coastal and estuarine engineering projects. Although the physically based sediment transport formulae are able to be constructed from first principles they often rely upon experimental data to aid in their formulation and for their verification.

In the complex situation of w+c flow the mean (current) component can be characterised by the depth averaged velocity V and the periodic component due to wave action by the bottom orbital velocity amplitude W. Combined flow conditions in the marine environment can be described as current dominated when the ratio W/V < 0.2 or wave dominated when

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[1]Section Manager, Sediments Research Group, HR Wallingford Ltd, Howbery Park, Wallingford, OXON OX10 8BA, UK

W/V > 0.2 (Soulsby and Humphery, 1990). Once waves are present they will enhance the entrainment of sand, by the so called stirring process, and hence increase the transport rate of sand over that due to the current alone. Under storm conditions in tidal channels or in the nearshore zone the waves can become the dominant entraining agent. The detailed mechanics of the entrainment process, and the resulting concentration profiles, will depend upon sedimentological factors, whether the waves and currents are small or large, and the value of the ratio W/V.

This paper presents some results from two field w+c sediment transport experiments that have been performed in two different nearshore environments, at Maplin Sands and at Boscombe in the UK. Previously Owen and Thorn (1978) and Grass (1981) have used a selection of the Maplin data to parameterise functions for the sediment transport rate under w+c. Whitehouse (1991), however, was the first to present profile data from these experiments (Boscombe).

The data provide information with which to examine the physical processes behind the entrainment of sand and the resulting near-bed concentration, the diffusion of sediment into the flow, and subsequently the rate of sand transport.

2. MEASUREMENTS

Detailed measurements have been made at two field sites to determine the vertical structure through the water column of hydro and sediment dynamic parameters. Over 350 measured profiles were obtained from the two experiments.

The first series of measurements were made in the Outer Thames Estuary between 1973 and 1975 from a free standing tower sited at the southern edge of Maplin Sands and adjacent to a deep water channel. The site was exposed to wind wave action and experienced strong tidal currents moving in and out of the estuary over a fine sand bed (d_{50}=0.141mm). These data were collected for the specific purpose of determining the effect of waves in enhancing current dominated sand transport, and also included data for the current alone condition.

The second series of measurements were taken under storm wave conditions in the surf zone at the seaward end of Boscombe Pier (1977-78). At this site, in Poole Bay on the south coast of the UK, the tidal streams are weak but can be enhanced under storm conditions by strong wind induced alongshore currents. The medium diameter sand present at this site was recorded as having a median size of around 0.200mm.

Background information and location maps for both of these experiments have been presented by Owen and Thorn (1978).

In both series of experiments an instrument package was mounted on a trackway to enable the vertical structure measurements to be made starting at 0.05m above the bed. Vertical profiles of the horizontal component of velocity were obtained using a self aligning propeller current meter at Maplin and at Boscombe from a 2 axis electromagnetic current meter (EM), oriented to obtain both the cross shore and alongshore components of velocity. The corresponding suspended sediment concentration profiles were obtained with a pump sampler device. The sand fraction concentrations (sediment larger than 0.04mm) were determined in mgl^{-1} as the dry mass of sediment contained in the volume of water that was sampled (20 litres).

Waves at Maplin were measured by a Waverider buoy sited 900m to the east of the tower and at Boscombe by the output from a pressure transducer mounted 1.25m above the bed. The wave velocity W at Maplin was calculated from the Waverider data and at Boscombe directly from the EM record.

At Maplin only mean velocities were recorded, averaged over 100 seconds, whilst at Boscombe waves and currents were sampled at 4Hz with record lengths of 1 minute or more.

3. HYDRODYNAMICS

The results of the flow measurements obtained from both experiments will be discussed further below.

3.1 Maplin data

The velocity measurements taken at this site have allowed the form of the velocity profile through the tidal cycle to be determined at half hourly intervals. An example of the data are plotted in Figure 1a (no waves) in which the numbers at the tops of the profiles indicate the chronological order through the deployment. The negative current velocities, on this and subsequent graphs, represent the measurements made on the flood tide and the positive values correspond to the ebb. The current speed has been assumed to be constant above the height of the topmost measured point and the top of each line has been plotted as to represent the water surface at the time that profile was measured. The locus of points thus formed provides a trace of the water level through the tide, varying by more than 4m, and shows the out of phase relationship between tidal amplitude and tidal currents typical of many estuaries (Dyer, 1973). On the whole the sequence of velocity profiles are well behaved and exhibit the characteristics of a tidal oscillatory boundary layer, with a mass flow asymmetry in the flood direction.

Similar datasets were obtained on 25 subsequent deployments during which wind waves were present. A detailed analysis of the velocity profiles allows for some influence of the waves on the current structure to be determined but these details will not be discussed any further here.

For practical purposes, however, Soulsby (1990, figure 10 and equation 23) has shown that an empirical current velocity profile appears to provide a reasonable approximation to the vertical structure of the tidal current for a number of estuary and continental shelf sites. The function is a modified version of the 1/7 power law, with constant velocity above mid depth

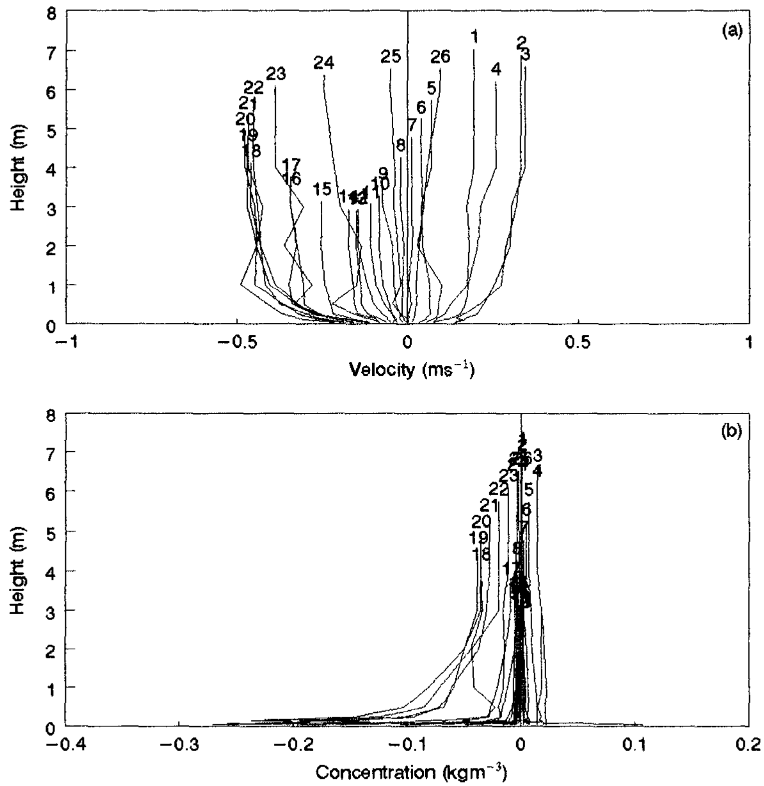

Figure 1. The evolution of (a) the tidal current velocity profile and (b) the sand concentration profile at Maplin Tower through a spring tide with no wave action (1 November 1973). Profiles 1-1 to 1-26

(Equation 1). The height above the bed z is non dimensionalised with the water depth h and the current velocity V_z at height z with V.

$$V_z=\left(\frac{z}{0.32h}\right)^{1/7}V \qquad 0\leq z\leq 0.5h \tag{1a}$$

$$V_z=1.07V \qquad 0.5h\leq z\leq h \tag{1b}$$

Five sets of profile data both with and without waves and for flood and ebb tides have been plotted with the empirical function in Figure 2 which confirms the form of Equation 1 on average. The data correspond to measurements made near to the peak excursion of the tidal velocity amplitude (Table 1). Although this profile shape will be unlikely to hold at times around slack water it can be used to approximate the vertical current structure for a large proportion of the tide.

3.2 Boscombe data

The EM data provide information both on the vertical structure and on the temporal variation in the velocity field for 26 deployments of the instrument package. An example of the time series data from Boscombe is plotted in Figure 3 showing the variation of the water surface elevation due to the passage of waves in 4.23m of water and the corresponding near bed velocities. The waves in the trace are typical of surf zone conditions producing the characteristic periodicity in the cross shore (x) velocity. The record for the y component of velocity depicts the turbulent alongshore current and that for the resultant velocity is mixed accordingly.

The vertical structure data at this location does not conform to the function employed in Figure 2. Above the bottom 5 or 10% of the water

Table 1. Physical parameters for velocity profiles displayed in Figure 2

Data	Velocity V (ms^{-1})	Wave velocity W (ms^{-1})	Water depth h (m)	Tide
1-3	0.303	0.000	6.59	ebb
2-12	0.251	0.038	7.30	ebb
1-22	0.422	0.000	5.75	flood
4-1	0.440	0.110	7.60	flood
5-7	0.656	0.091	5.03	flood

column the time averaged current velocity becomes approximately equal to the depth averaged value, at least to the height of the measured data which is equivalent to about 70% of the water depth for most cases. The data also indicate a veering of the velocity vector through the water column.

4. SEDIMENT DYNAMICS

The time averaged sediment concentration measurements will be discussed below for both experiments.

4.1 Maplin data

As with the velocity profile measurements the temporal variation in the vertical sand concentration profiles at this site with no wave action can be visualised (Figure 1b). For convenience, the data have been plotted in the same form as the velocity data in Figure 1a. Some interesting features can be observed by following the chronological sequence through the tide from slack water, profile 8.

The concentrations remain low for small flood (negative) velocities but increase markedly as the current velocity exceeds $0.3ms^{-1}$ (profile 16), the concentration at 0.05m increases from $0.045kgm^{-3}$ at profile 16 to $0.196kgm^{-3}$ at profile 17. Although the magnitude of the velocity has not changed

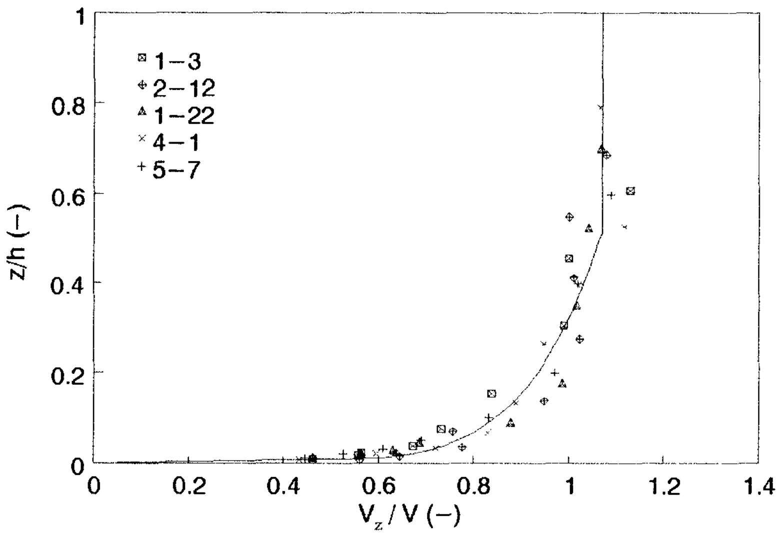

Figure 2. Comparison of selected Maplin Tower velocity profile data with the empirical function presented by Soulsby (1990)

appreciably in the half hour interval between these two observations the magnitude of the near bed sand concentration has increased by a factor of 4. The near bed concentration reaches an equilibrium at profiles 18 to 21, equal to about $0.270kgm^{-3}$.

Thereafter, and for the ensuing ebb tide, the near bed concentrations decrease rapidly due to the downward settling of the sand in suspension until a near vertically uniform distribution is achieved. No significant additional sand entrainment takes place on the ebb tide with the depth averaged velocity not exceeding $0.3ms^{-1}$. The data provide clear evidence to support the use of a threshold velocity for the entrainment of sand into suspension, for the lag in the response of the concentration profiles with increasing flow velocity and for a hysteresis in the velocity concentration correlation.

The influence of waves on the flood tide concentration profiles can

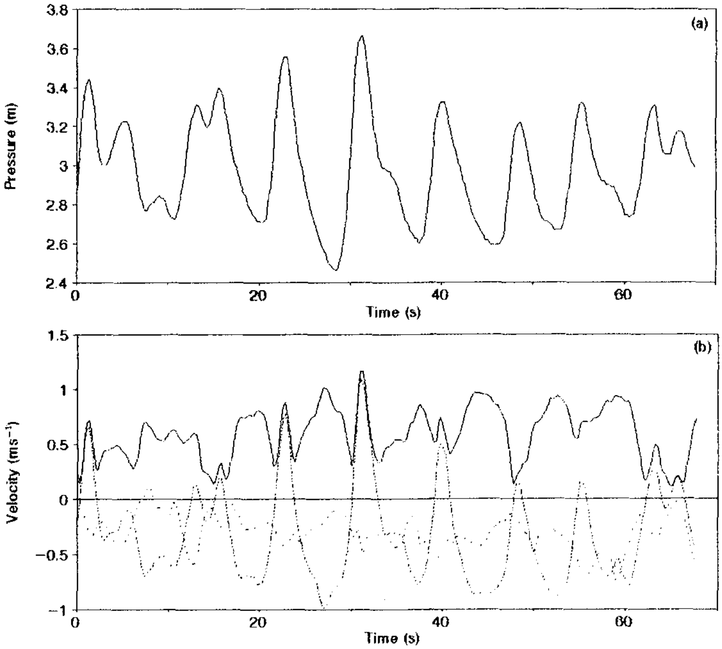

Figure 3. Time series records from the surf zone at Boscombe for: (a) the water surface elevation expressed in m of water and, (b) the x (stippled line) and y (dashes) components of fluid velocity and their resultant (solid line). The velocity measurements were taken at 0.05m above the bed starting at 1523hrs on 15-11-1978. The mean water level on (a) was at 2.98m.

be seen in Figure 4 for similar values of velocity V and water depth, one for the current alone case and one with wave activity (W=0.072ms^{-1}, T_z=2.8s). Under wave enhanced conditions (W/V=0.214) the near bed sand concentration is increased by a factor of 2.7 over the current alone case due to the stirring action of the waves. Additional turbulence diffusing up from the wave boundary layer serves to enhance the sediment load and both factors produce an increase in the depth integrated flux of sand q_+ (see Section 6) by a factor 1.3.

4.2 Boscombe data

The sediment concentration measurements at Boscombe relate only to w+c conditions. Vertical profile data are presented in Figure 5 for two different wave dominated conditions with similar values of the current velocity, water depth and wave period, about 6.5 seconds, but different wave heights H_s. Under the larger wave conditions the near bed sediment concentration is enhanced by more than a factor of 10 and the magnitude of q_+ by a factor 6.2 above that for the smaller wave case.

Nielsen (1979) has shown in laboratory measurements that the magnitude of the near bed concentration under waves is a function of the bottom boundary layer and independent of breaker type. However, under broken waves in the surf zone there will be two contributions to the turbulence field, one from the wave boundary layer and a second from the downwards dissipation of surface generated turbulence contained within the broken wave as discussed, modelled and verified with experimental data by

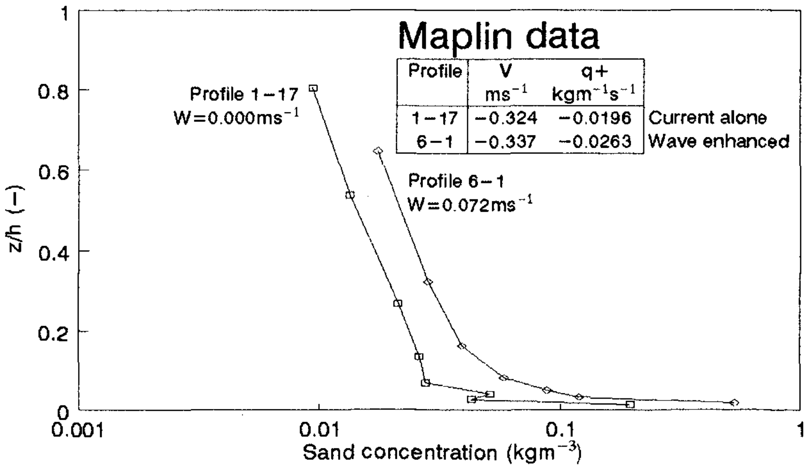

Figure 4. Sand concentration profiles obtained from Maplin under current alone and wave enhanced conditions

Deigaard et al. (1986). At Boscombe the contribution of surface turbulence to supporting the suspension will be appreciable.

For similar values of the current velocity, the data presented in Figure 5 show that an increase in the magnitude of the near bed concentration is produced by the addition of the stronger wave component. The additional contribution to the turbulence energy field from the broken wave, the relative strength of which is symbolised by the ratio H_s/h, will be important in defining the suspension profiles. This particular case is complicated by the differences between the median grain sizes of the two suspension profiles.

5. SEDIMENT ENTRAINMENT

The relationship between the flow conditions and the near bed sediment concentration will now be considered. Sand concentration data measured at a height of 0.1m above the bed has been used for both experiments to enable a comparison to be made, denoted $C_{0.1}$.

5.1 Maplin data

The data for the variation of $C_{0.1}$ with the depth averaged current velocity have been plotted in Figure 6. To enable the effect of the waves on the concentration to be viewed the data have been banded in terms of the wave velocity W. Current alone measurements are plotted as W=0 and are indicated by the thick black line, the other data are plotted for increasing values of W. The measurements clearly show the effect that waves have in

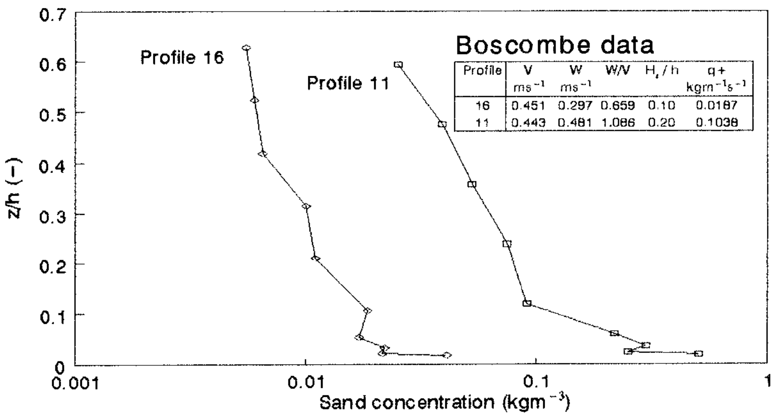

Figure 5. Sand concentration profiles obtained from Boscombe under two different wave dominated conditions

enhancing the near bed sand concentration over a wide range of current velocities.

In some cases, however, the sand concentration is reduced below its current alone value over the range of measured current alone values ($V<0.5ms^{-1}$). This is not surprising given the potential for scatter in sediment transport measurements. Van Rijn (1984), for example, reports the results of an earlier analysis of well controlled steady flow flume measurements in which he found deviations in the measured total load transport rate by up to a factor of 2 for similar conditions. It is concluded that the overall trend of the data presented in Figure 6 is encouraging.

5.2 Boscombe data

Whitehouse (1991) reported that the near bed concentration of sand was correlated more closely with the magnitude of the wave velocity W than with the current velocity V which had been found at the Maplin site. Here we have plotted the $C_{0.1}$ data from Boscombe in Figure 7 on the same axes as the Maplin data in Figure 6 and banded in the same fashion.

Although a direct comparison of the two data sets cannot be made, because we do not have any current alone data from this site with which to

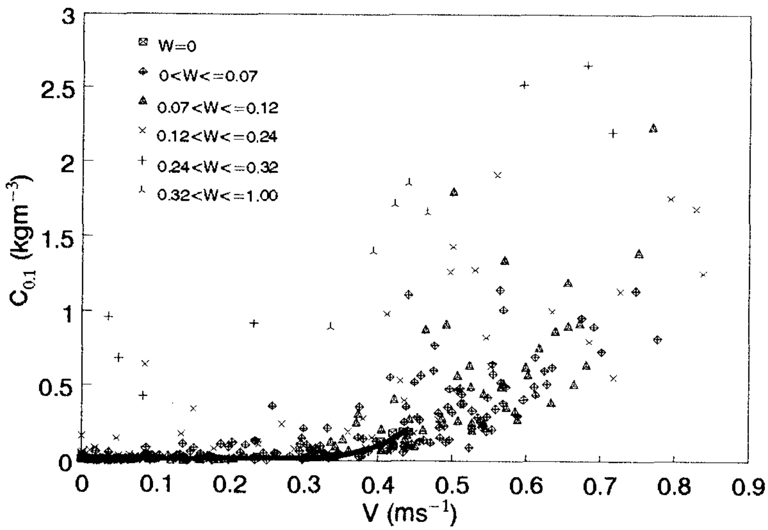

Figure 6. The variation in $C_{0.1}$ the sand concentration at 0.1m above the bed with current velocity V at Maplin (all data), banded in terms of the wave velocity amplitude W (ms^{-1})

assess the grain size difference at the two sites, the larger wave velocities produce higher concentrations of sand near to the bed for a given value of V. However, the large wave orbital velocities at this site do appear to have a dominant effect in determining the entrainment of sand from the bed.

5.3 Vertical mixing

Once the sediment has been entrained from the bed the w+c concentration profiles for both experiments can be approximated by an exponentially decaying concentration profile over the bottom 10% of the water column, ie constant eddy viscosity.

6. SEDIMENT TRANSPORT RATE

The suspended sediment transport rate was determined by integration of the sand flux profiles (V_zC_z product) through the water depth, assuming that the flux goes to zero both at the bed (z=0) and also at the water surface (z=h).

6.1 Maplin data

The sediment transport rate q_+ has been plotted in Figure 8a to show the variation with the current velocity, the data has been banded in terms of W. This shows that q_+ increases with increasing V and in addition that the transport rate is enhanced by the addition of waves, especially obvious for the highest range of W values. However, the scatter in the data is noticeable at

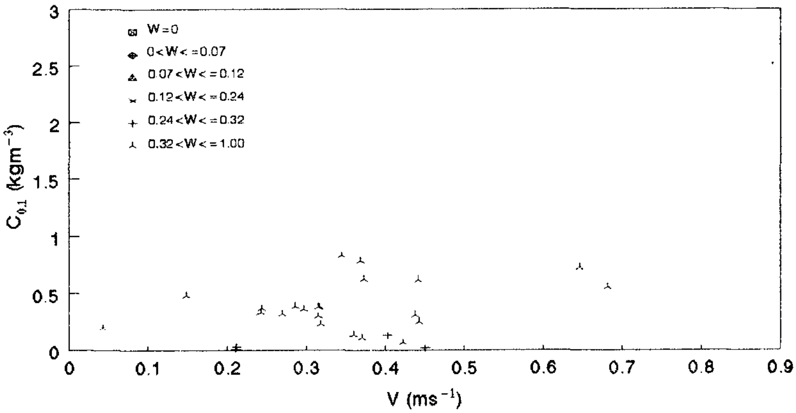

Figure 7. The variation in sand concentration at 0.1m above the bed with current velocity at Boscombe (all data), banded in terms of the wave velocity amplitude W (ms^{-1})

low values of the current velocity ($V<1E\text{-}1 ms^{-1}$) with the transport rate also appearing to be reduced below the current alone value. Further investigation of the data for those periods with small current velocities is warranted, ie during which non equilibrium conditions prevail.

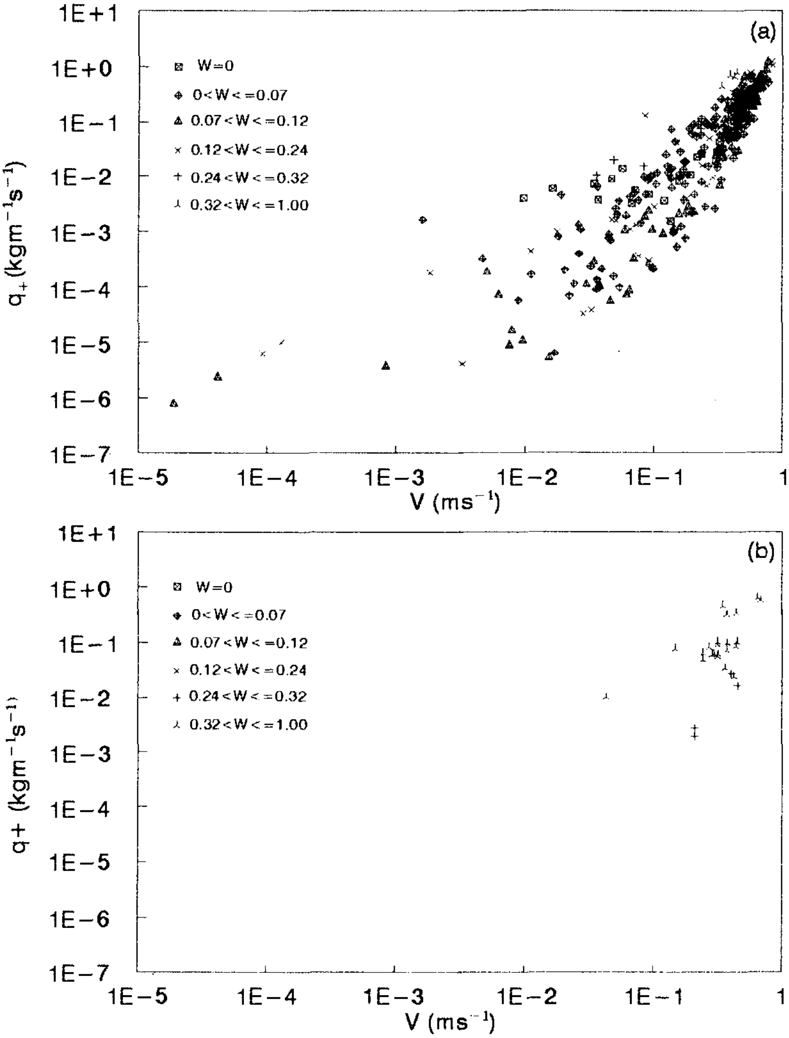

Figure 8. The relationship between the depth integrated suspended sediment transport rate and the current velocity: (a) Maplin data, (b) Boscombe data, banded in terms of the wave velocity amplitude W (ms^{-1})

Selected data of this form have been collapsed onto a single curve using the concept of an equivalent current velocity (Grass, 1981) or a sand flux multiplier (Owen and Thorn, 1978).

6.2 Boscombe data

The transport rate data from Boscombe have been plotted in the same axes as for Maplin (Figure 8b). The two ranges of W banded data show an increasing transport rate with increasing current velocity. However, the limited data set available at Boscombe also indicates a strong positive correlation between the wave velocity and the transport rate (Whitehouse, 1991).

7. CONCLUSIONS

This paper has presented the results from two field experiments performed to obtain measurements of suspended sand transport under wave and current action. The data illustrate the potential for waves to increase the near bed suspended sediment concentration above that resulting from the action of a current alone. As a consequence, more sediment is available to be mixed into the water column. This can be accomplished easily with the additional turbulence generated from the wave boundary layer and with the surface contribution to the turbulence levels from broken waves in the surf zone.

The sand transport data obtained from Maplin Sands during equilibrium periods of the tide can be used immediately in further work. The complex situation imposed at non equilibrium times in the tidal cycle, caused by the advection of suspended sand and other processes, requires an analysis in terms of more advanced physical modelling concepts.

The Maplin and Boscombe data taken in combination will be useful in enhancing the value of further analyses of w+c sediment transport because of the different environments, w+c conditions and sediment conditions covered.

8. ACKNOWLEDGEMENTS

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