ACOUSTIC MEASUREMENTS OF VORTEX RIPPLE ENTRAINMENT AND SEDIMENT DIFFUSIVITY OVER A SANDY RIPPLED BED UNDER WAVES

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\textbf{Abstract:} Measurements of the flow, suspended sediments and bedforms have been collected in the large Delta Flume facility of Delft Hydraulics in the Netherlands. The flume is 230 m in length, 5 m in width and 7 m in depth. The facility allowed field scale conditions to be generated in a controlled manner. Utilising an acoustic backscatter system, ABS, and an acoustic ripple profiler, ARP, in conjunction with more conventional measurements, studies have been made of sediment entrainment over ripples under regular waves. Under regular waves, over steep ripples, it is generally considered that vortex ejection at flow reversal is the main mechanism for entrainment. In small scale flumes with sharp crested ripples, vortices have been observed. However, there are relatively few observations of the mechanism at field scales. The mechanism is examined here using observations of intra-wave intra-ripple entrainment collected in the Delta flume. In conjunction with the vortex measurements an examination of the form of the sediment diffusivity is carried out and the links between its form and the vortex model is discussed.

\textbf{Keywords:} acoustics, backscattering, suspensions, sediments, ripples, vortex, diffusivity
1. BACKGROUND

Over large areas of the continental shelf outside the surf zone, sandy seabeds are covered with wave formed ripples. If the ripples are steep, the entrainment of sediments into the water column, due to the waves, is mainly considered to be due to the generation of vortices. This process is illustrated in figure 1. A spinning parcel of sediment laden water, $v_1$, is formed on the lee side of the ripple at the peak positive velocity in the wave cycle, as shown figures 1a-1b. This sediment rich vortex is then thrown up into the water column at flow reversal, figure 1c-1d, carrying sediment well away from the bed and allowing it to be transported by the flow. At the same time a sediment rich vortex, $v_2$, is being formed on the opposite side of the ripple due to the reversed flow. As shown in figures 1d-1f, $v_2$ grows, entrains sediment, becomes detached and moves over the crest at the next flow reversal carrying sediments into suspension. The main feature of the vortex mechanism is that sediment is carried up into the water column twice per wave cycle around flow reversal.

![Figure 1. Schematic of vortex entrainment of sediment over a rippled sandy bed. The horizontal arrow at the top of each figure represents the near-bed velocity](image)

2. EXPERIMENTAL FACILITY

To study this fundamental process of sediment entrainment, experiments were conducted in one of the world’s largest manmade channels, specifically constructed for such sediment transport studies, the Delta Flume in the Netherlands. The flume, shown in figure 2a, is 230 m in length, 5 m in width and 7 m deep and it allows waves and sediment transport to be studied at full scale. A wave maker at one end of the flume generates the waves which propagate along the flume over a sandy bed and dissipate on a beach at the opposite end. The bed in the present experiments comprised coarse sand, $d_{50}=330 \mu m$, which was located approximately halfway along the flume in a layer of thickness 0.5 m and length 30 m. In order to make the acoustic and other auxiliary measurements an instrumented tripod platform was developed; this is shown in figure 2b. The tripod STABLE II (Sediment Transport And Boundary Layer Equipment) used an acoustic backscatter system, ABS, to measure profiles of particle size and concentration, a pencil beam acoustic ripple profiler, ARP, to measure the bedforms and electromagnetic current meters, ECM’s, to measure the horizontal and vertical flow components. Figure 2c shows
a wave propagating along the flume with STABLE II submerged in water of depth 4.5 m, typical of coastal zone conditions.

Figure 2. (a) Photograph of the flume used to collect the measurements. (b) The instrumented tripod platform, STABLE II, used to make the acoustic measurements. (c) A wave propagating down the flume.

The platform and the instrumentation on STABLE II are shown in figure 3. To measure the suspended sediment profiles a triple frequency, 1.0 MHz, 2.0 MHz and 4.0 MHz, acoustic backscatter system, ABS, was employed. This provided 128 Hz measurements of the backscattered signal, at 0.01 m intervals from the bed, up to the location of the acoustic transducers mounted at a mean height of 1.24 m above the bed. To augment and calibrate the ABS measurements, pumped samples were collected at ten heights above the bed, between 0.05 m-1.55 m. As well as using the ABS to locate the bed position, an acoustic ripple profiler, ARP, was used to make measurements of ripple height and wavelength along a 3 m profile of the bed over time. To measure the hydrodynamics, three pairs of electromagnet current meters, ECM, were located at heights of 0.30 m, 0.60 m, and 0.91 m above the bed.

Figure 3: Instrument platform STABLE showing the location of the ABS, ARP, ECMs and pumped samples
3. OBSERVATIONS

3.1 Vortex entrainment
To investigate the vortex entrainment process it was necessary to establish at the outset whether or not the surface waves were generating ripples on the bed in the Delta Flume. Using the ARP a 3m transect of the bed was measured over time. The results of the observations over a 90 minute recording period are shown in figure 4. Clearly ripples were formed on the bed and the ripples were mobile. To obtain flow separation and hence vortex formation requires a ripple steepness (ripple height/ripple wavelength) of the order of 0.1 or greater. An analysis of the observations showed this was indeed the case.

![Figure 4. ARP measurements of the sand ripples on the bed.](image)

Using the ABS some of the most detailed measurements of sediment transport recorded over a rippled bed at full scale were captured. These measurements from the Delta Flume are shown in figure 5. The images shown were constructed over a 20 min period as a ripple passed beneath the ABS. The suspended concentrations at different locations on the ripple, at the same (four) velocity instants during the wave cycle, were combined to generate the respective images. The length and direction of the arrows in the figure gives the magnitude and direction of the wave velocity. Comparison of figure 5 with figure 1 shows substantial similarities. In figure 5a there can be observed the development of a high concentration event at high flow velocity above the lee slope of the ripple, \( v_1 \). In figure 5b as the flow reduces in strength, the near-bed sediment-laden parcel of fluid travels up the lee side of the ripple towards the crest. As the flow reverses this sediment laden fluid parcel, \( v_1 \), travels over the crest and expands. As the reverse flow increases in strength, figure 5d, the parcel \( v_1 \) begins to lift away from the bed and a new sediment-laden lee vortex, \( v_2 \), is initiated.
Figure 5. Acoustic imaging of suspended sand entrainment over a rippled bed due to waves, at four phases of the wave cycle. The length of the white arrow in each plot gives the magnitude and direction of the near-bed wave velocity.

These acoustic observations have been used to assess a recently developed model of sediment transport over vortex ripples. In order to capture the essential features of this data within a relatively simple 1DV (one-dimensional in the vertical) model, the data has first been horizontally averaged over one ripple wavelength for each phase instant during the wave cycle. The resulting pattern of measured sediment suspension contours is shown in the central panel of figure 6, while the upper panel shows the oscillating velocity field measured at a height of 0.3 m above the bed. The concentration contours shown here are relative to the ripple crest level, the mean (undisturbed) bed level being at height $z = 0$. The measured concentration contours presented in figure 6 show two high concentration peaks near the bed that propagate rapidly upwards through a layer of thickness corresponding to several ripple heights. The first, and strongest, of these peaks occurs slightly ahead of flow reversal, while the second weaker, and more dispersed peak is centred on flow reversal. The difference in the strengths of the two peaks reflects the greater positive velocity that can be seen to occur beneath the wave crest (time=0 s) than beneath the wave trough (time=2.5 s). Between the two concentration peaks the sediment settles rapidly to the bed. The underlying mechanism of sediment entrainment by vortices shed at or near flow reversal is clearly evident in the spatially-averaged measurements shown in figure 6.
Figure 6. Measurement and modelling of suspended sediments with height $z$ above a rippled bed under a 5 s period wave.

Any conventional ‘flat rough bed’ model that attempts to represent the above sequence of events in the suspension layer runs into immediate and severe difficulties, since such models predict maximum near-bed concentration at about the time of maximum flow velocity, and not at flow reversal. Here therefore, using a recently developed 1DV model, it has been attempted to capture these effects realistically through the use of a strongly time varying eddy viscosity that represents the timing and strength of the upward mixing events due to vortex shedding. The resulting concentration contours in the present case are shown on the lower panel of figure 6. The essential two-peak structure of the eddy shedding process can be seen to be represented rather well, with the initial concentration peak being dominant. The decay rate of the concentration peaks as they go upwards is also represented quite well, though a phase lag develops with height that is not seen to the same extent in the data. Essentially the detailed acoustic observations of sediment entrainment under waves over ripples of moderate steepness, have begun to establish a new type of 1DV modelling, thereby allowing the model to go on to be used for practical prediction purposes in the rippled regime, which is the bed form regime of most importance over wide offshore areas in the coastal seas.
3.2 Sediment diffusivity

The sediment diffusivity characterises the rate of upward sediment flux away from the bed, here including the effects of both (convective) vortex entrainment and also turbulent diffusion. To obtain estimates of the sediment diffusivity, $\varepsilon_s$, the standard formulation based on the cycle-mean concentration, $C$, and its vertical gradient, $dC/dz$, was adopted:

$$\varepsilon_s = -\frac{w_0 C}{dC/dz}$$

(1)

where $w_0$ is the mean settling velocity of the sediment in suspension and $z$ is the height above the bed measured from the ripple crest. Measurements were collected for regular waves of period 5 s, with wave heights between 0.8 m-1.3 m. For purposes of interpretation, the data has been plotted in a normalised form based on the following parameterisation; $\varepsilon_s/(U_0 \eta_r)$ and $z/\eta_r$, where $U_0$ is the wave orbital velocity at the bed and $\eta_r$ is the height of the ripples on the bed. Figure 7 shows the normalised sediment diffusivity profile with normalised height above the bed.

![Figure 7. Measurements of the normalised sediment diffusivity with normalised height above the bed. Red dots are for the individual wave conditions and the black dots are an average over all the wave conditions.](image)

For the regular waves, the profile of diffusivity is relatively uniform near the bed, $z/\eta_r = 0.5-4$, though there is some reduction below $z/\eta_r = 0.5$. The thickness of the layer in which the diffusivity remains constant corresponds to about 4 ripple heights in this case. Above approximately $z/\eta_r = 4$ the diffusivity starts to increase linearly with height, though there is scatter in the data. Physically the observations are interpreted as corresponding to a lower vortex-dominated layer of thickness a few ripple heights, in which the process of eddy shedding gives rise to efficient, vertically uniform, mixing of sediment. Above this height the vortices break down, and normal turbulent diffusion concepts become dominant. In this upper turbulent layer, the mixing length scale is expected to increase with height and the sediment diffusivity is therefore expected to increase with height also. This constant-linear two layer structure is in contrast to the generally accepted picture for...
plane beds, above which the sediment diffusivity increases linearly with height from the bed level itself.

4. CONCLUSIONS

The aim of the paper has been to illustrate the application and use of acoustics in the study of sediment transport under waves over a rippled bed. Intra-wave, intra-ripple measurements of suspended sediments were obtained and these were used to investigate the concept of vortex entrainment over a steeply rippled bed. The observations indicate the vortex mechanism was occurring. By averaging the data over the ripple, the ripple averaged suspended concentration, with the phase of the wave, was formed and this has been used to assess a recently developed sediment transport model which combined vortex entrainment near the bed, with a turbulence closure scheme above the vortex layer. The model and the observations were close agreement with each other. Finally the vertical spatial resolution of the ABS was utilised to form detailed profiles of the vertical sediment diffusivity. This showed results quite different from a flat bed, with uniform sediment diffusivity in the bottom few ripple heights above the bed, above which mixing increased with height above the bed.

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REFERENCES