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A new, high-resolution 'depth of disturbance' instrument (SAM) for use in the surf zone.

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ABSTRACT

The calculation of the degree of sediment disturbance through wave action in the surf and swash zone has been examined at various levels in recent years using a number of empirical techniques. Quantifying 'depth of disturbance'(also know as sediment mixing depth) enables a better understanding of nearshore processes, where interaction between sediment and surf zone wave action is complex. Better understanding of how sediment responds to given surf and swash zone parameters is paramount in examining a number of phenomena such as natural beach evolution, sediment movement around engineering structures, the design and planning of beach renourishment schemes, and the monitoring of pollution behaviour. Previous empirical studies have concentrated their efforts in various methodologies such as the use of sediment tracers to mark the sediment, depth of disturbance rods deployed over a tidal cycle and the use of plug-holes filled with marked sediment.

All efforts at estimating sediment disturbance in the field to date have resolved their measurements only after a complete tidal cycle and have been unable to measure processes during the actual perturbations caused by wave action within the tidal event, an essential period of activity to understand bed elevation patterns. This paper seeks to address the present shortfall in methodology with the design and construction of a new, high resolution, vertical measurement system. The new instrument, a Sediment Activity Meter (SAM), characterises surface elevation changes in the sediment bed of the surf zone at a given deployment location at approximately 2 minute sampling intervals. This technique will, for the first time, enable realistic comparisons to be made between bed change and the main forcing variables of the system during a tidal cycle.

The paper mainly outlines the basic design of the new field instrument and describes, for the first time, surf zone seabed elevation changes (at a single point) measured at approximately 2-minute intervals alongside corresponding wave parameters and water depths within the surf zone. The field trials took place on a high-energy beach system in Northern Ireland.

ADDITIONALINDEXWORDS: *Surf zone, depth of disturbance, waves, high resolution.*

INTRODUCTION

The calculation of the degree of sediment disturbance through wave action in the surf and swash zone has been studied at various levels in recent years with a number of empirical techniques (e.g. WILLIAMS, 1971; SUNAMURA and KRAUS, 1985, JACKSON and NORDSTROM, 1993; TABORDA *et al*., 1994). Quantifying 'depth of disturbance' (also know as sediment mixing depth) enables a better understanding of nearshore processes, where interaction between sediment and surf zone wave action is complex. Better understanding of how sediment responds to given surf and swash zone parameters is paramount in examining a number of phenomena. These include natural beach evolution, sediment movement around engineering structures (FUCELLA and DOLAN, 1996), the design and planning of beach renourishment schemes, as well as the monitoring of pollution behaviour (DOLPHIN *et al*., 1995). Sediment depth of disturbance (DOD) has been attributed fundamentally to wave parameters and accompanying beach characteristics. Various physical variables have been examined in this problem which include breaker height, pressure gradients, beach slope, effective Shield's parameters, sediment characteristics, as well as bedform migration over the sediment body (SHERMAN *et al*., 1993). Previous empirical studies have concentrated their efforts in various methodologies, including the use of tracers to mark the sediment (KRAUS *et al*., 1982; KRAUS, 1985), depth of disturbance rods deployed over a tidal cycle (SHERMAN *et al*., 1993) and the use of plug holes filled with marked sediment (SHERMAN *et al*., 1994; FERREIRA *et al*., 1998). Definitive papers such as KRAUS (1985) and SUNAMURA and KRAUS (1985) have identified, through tracer experiments, the average mixing depth for the surf zone of a broad range of sites and produced the following linear expression:

$$Z^m = 0.027H_b \quad \textbf{(1)}$$

Where Z_m = mixing depth of the sediment in the surf zone, H_b is breaker height.

Equation (1) was derived from a series of experiments conducted over a selection of mainly dissipative beaches. Other work (CIAVOLA *et al*., 1997) has shown the equation to alter its constant dramatically, increasing by a factor of ten under reflective beach conditions:

$$Z_m = 0.27H_b \quad \textbf{(2)}$$

Attempts at estimating sediment disturbance to date have resolved their measurements only after a complete tidal cycle and therefore have been unable to measure processes during the actual perturbations caused by wave action within the tidal event, an essential period of activity to understand bed elevation patterns.

In a wider context, surf zone morphodynamic research has dealt with the effect of varying water level in wave action (i.e. initiation and modes of sediment transport and induced morphodynamics). Current thinking in this field comes from a variety of studies that demonstrate the importance of wave height sensitivity and the control that water depth exerts on sediment disturbance. MASSELINK and SHORT (1993), MASSELINK and BLACK (1995), MALVAREZ *et al*., (2001), GREEN and MACDONALD (2001) have highlighted, within different environments, the crucial role of water level in sediment distribution and transport. Mixing depth has commonly been measured as the net variation over at least one complete tidal cycle. Valuable information is thus being overlooked in relation to wave penetration in the water column. Wave induced stress acting on bed sediments is small under the effects of high frequency waves, typical of shallow water phases (i.e. begin of rising or end of falling tide), because the orbital motions cannot penetrate to the bed. At an optimum water level, wave orbital velocity penetrates the water column making wave height (and associated energy and stress) more effective in moving sediments. This optimum water level has been described for low energy scenarios such as estuarine environments (MALVAREZ *et al*., 2001; GREEN and MACDONALD, 2001) and it therefore seems logical that including measurements of DOD combined with simultaneous in situ wave parameters can provide a way of advancing knowledge in this field. Empirical measurements are inherently easier to conduct in low energy environments; SAM, however, has been designed to withstand very energetic wave climates even in the turbulent surf zones of North Atlantic beaches combining robustness with sufficiently high resolution and sensitivity.

This paper seeks to address the present shortfall in methodology with the design and construction of a new, high resolution, vertical measuring system of the sea bed. The new instrument, a Sediment Activity Meter (SAM), characterises surface elevation changes in the sediment bed of the surf zone at a given deployment location at 2 minute sampling periods. Sampling duration of the instrument is limited to 70 hours by DC power demands and the degree of bed change (larger change results in longer feed out of rod support cable and thus increased power consumption). Two complete semi-diurnal tidal cycles can however, be examined. This technique will, for the first time, enable realistic comparisons to be made between bed change and the main forcing variables of the system during a tidal cycle. As well as addressing the inherent problem of poor temporal sampling resolution at any given point, a number of these devices deployed across an active surf zone will also enable better examination of any spatial patterns of bedforms changes during tides.

The positioning of deployment of the apparatus also enables estimation of wave and DOD variation in the surf zone rather than in the swash zone which is typically the only area accessible using other low resolution methods (it is not required that the experiment is started in exposed intertidal zones of the beach to deploy tracers and/or position pins etc.).

This paper largely outlines the basic design of the new instrument and examines some preliminary, yet interesting, results from a field trial that took place on a high-energy beach system (intermediate morphodynamic beach state during the experiment) in Northern Ireland.

STUDYAREA

The experiment was conducted on Runkerry strand located on the north coast (county Antrim) of Northern Ireland (Irish grid ref. C935425). The beach can be described as a 1.2 km long, high energy system, exposed to a northwest wave direction (Fig.1). The system is bounded by two tertiary basalt headlands at each end of the embayment, with the river Bush discharging into its southern section.

The beach is located within a high energy, swell wave-dominated environment under a micro-tidal regime (mean spring tidal range of 1.54m) and represents one of the highest energy beach systems along the Northern Ireland coastline. Swell waves from the Atlantic have a modal approach direction of around 280° when travelling through the Malin Sea but most undergo considerable refraction before reaching the Runkerry site. Previous work on annual wave data 20 km offshore has shown a typical modal significant wave height (Hs) in the range of 2-3m (MALVAREZ *et al*., 1995) and modal zero crossing period (T_z) of about 8.5 seconds (CARTER, 1991).

Nearshore modification of waves at Runkerry is largely dictated by the seasonal adjustments to the beach and nearshore areas that undergo dramatic morphological alteration throughout an annual time frame. Previous profile studies at the site (SHAW, 1985, 1981; MALVAREZ *et al*., 1995) have shown a general beach level reduction in volume (covering the inter- and supra-tidal area) during the winter months between November to February and then a beach rebuilding phase occurring after June to early November. The scale of beach level changes also varies considerably along the beach and is probably due to the presence of local features such as the emerging river Bush and isolated rock outcrops effecting wave refraction patterns and energy delivery to the shore.

MALVAREZ *et al*., (1995) have shown, using the wave propagation model HISWA (HOLTHUIJSEN *et al*., 1989),

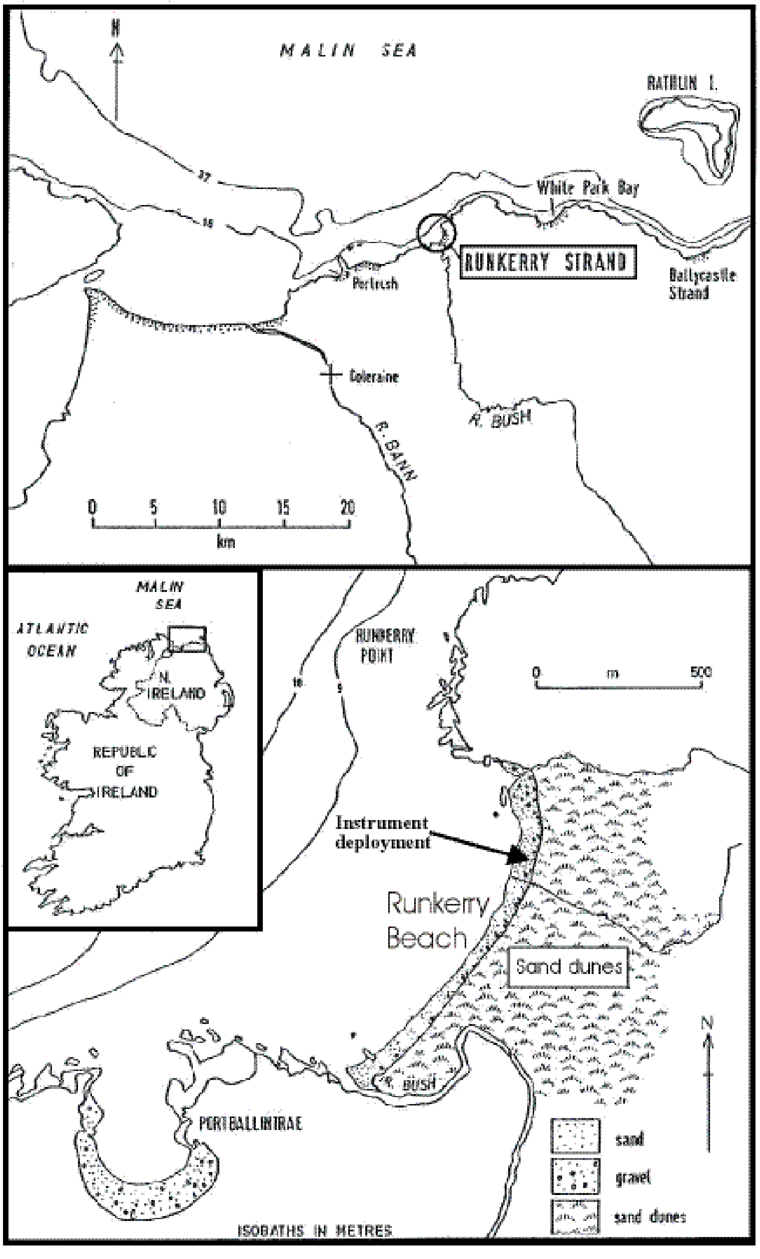

Figure 1. Site location and position of the SAM instrument deployment.

that deep water wave direction is largely insignificant at the site with wave approaches with a N, NW and W direction having close similarity in terms of their energy dissipation magnitude and direction. This demonstrates almost complete wave refraction within the bay with a higher significance attached to wave height and period parameters for beach morphodynamics.

METHODOLOGY

Sediment Activity Meter (SAM) design

The new instrument design is based around a framework housing, fixed into the sediment bed on a central mast, supported by guy wires and positioned within the surf zone (Fig. 2). An automated vertical bar, held out from the main vertical mast by horizontal support arms, is raised up and down at set intervals through the action of an electrical motor and is controlled through a PIC micro-controller (Fig.3). The end of the bar has a conical contact pad, suitably weighted internally to pull the bar down through the water column. At the start of a run, a manual power switch activates the bar mechanism. The bar then lowers itself through the action of a pulley and suspension cord (with no coiling memory and with a breaking strain of 22.68 kg) until it makes contact with the sediment bed, whereupon a highly sensitive tension sensor micro-switch in the control box detects a slack in the cord, and triggers the pulley to stop. The degree to which the cord has unwound (and therefore bed change) is recorded electronically using a voltage reading, whereby the greater the voltage the greater the cord feed out. The number of pulley revolutions and hence distance (height) through which the measuring rod has dropped is thus recorded. For its maximum amount of travel (sediment deflation of 0.30 m) from its rewound starting point, the bar takes 24 seconds to drop. Any sediment build-up present will result in less travel time. At the sediment contact point there is then a 1-second delay and the cord is rewound back again to recede into protective tubing. The base of the bar's conical foot makes contact with any new deflated or accreted sediment surface, which is recorded digitally each time the bar is lowered, thus giving bed elevation information. The design is configured to allow bed elevation measurements to be made at various time intervals from a minimum of 16 seconds up to a maximum of 128 seconds (plus travel time for rod to drop) as in this case, and stored in a data logger on the top of the mast in a waterproof compartment for later downloading.

The vertical extent to which the instrument is able to measure change is limited by the internal pulley diameter and the amount of bar exposed to wave action (too much and damage may occur in high energy environments) but in this case was set to record +/- 15 cm, giving a total possible vertical envelope of 30 cm. Later designs may extend this vertical range. During the experiment diving observations showed little or no scour disturbance occurring around contact point of the bar's foot and the sediment surface (fig.4). The foot remains only a short time (1 second) on the sediment surface before being rewound again, greatly assisting in lowering disturbance potential.

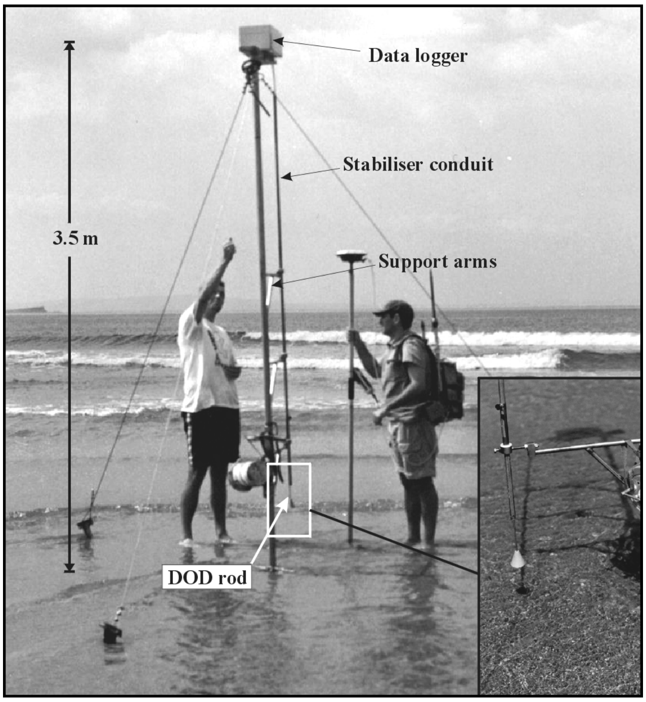

Figure 2. Main SAM instrument in the field at low tide. Inset shows a closer view of the main foot of SAM which conducts the DOD measurements. All circuitry is contained in a water tight housing on top of the mast.

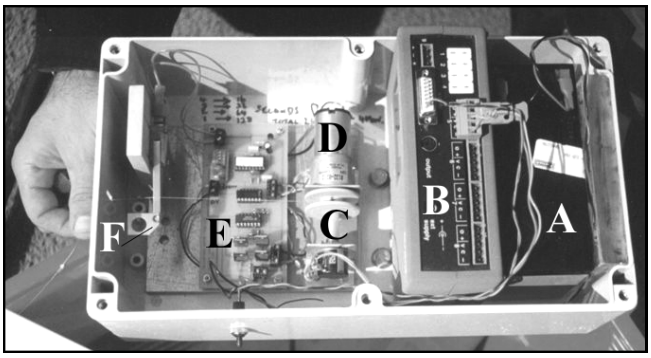

Figure 3. Interior of the electronic control box. A – 12v battery, 7 Ah; B – Data logger; C – pulley wheel for cord; D – motor; E – control circuitry; F - Tension sensor micro-switch which detects slack in the cord upon contact with the sea bed.

Instrument deployment

The SAM instrument was deployed on 23rd May 2001 on Runkerry beach in a nearshore mid-intertidal position (fig.1) with sampling beginning slightly after low tide. The total bed elevation data examined as part of this paper amounted to over 5 hours, taking in low to high tide and also part of the falling tide. A DOBIE wave recorder (GREEN, 1998) was installed in a weighted holding frame, approximate 5 metres from the base of the SAM in a seaward location, with its pressure transducer at approximately 0.5m elevation from the initial sediment surface. The time clock of the DOBIE was synchronised with the SAM logger and set up to sample wave characteristics every 6 minutes. The DOBIE sensor records hydrostatic pressure at a sample interval of 10Hz with 128 points per burst. Pressure is then converted into mean water depth using the hydrostatic equation and assuming a nominal atmospheric pressure (1000mb) and water density (1.025 g/cm^3). Burst averaged wave parameters are obtained at each 6 minute interval. Data from both instruments were downloaded separately after the experiment to a laptop computer.

A DGPS point (accuracy +/- 1.0 cm in the vertical) of the beach elevation was taken both before and after the experiment of the surface measurement point of the SAM. This allowed a net change in surface elevation to be examined at this point.

RESULTS

Changes in bed elevation between two monitoring periods (approximately every 140 s) are calculated by subtracting a preceding bed measurement from the next elevation result to get net change during that time. These are shown in figure 5 and are plotted alongside corresponding significant wave height and water level (tide) recorded from the DOBIE during the same period.

Figure 5 shows remarkable variation in bed elevation during the experiment but displays a general increase in total bed height of approximately 11.0 cm. This corresponds to a simultaneous increase in both water level (incoming tide) and significant wave heights acting on the sediment bed.

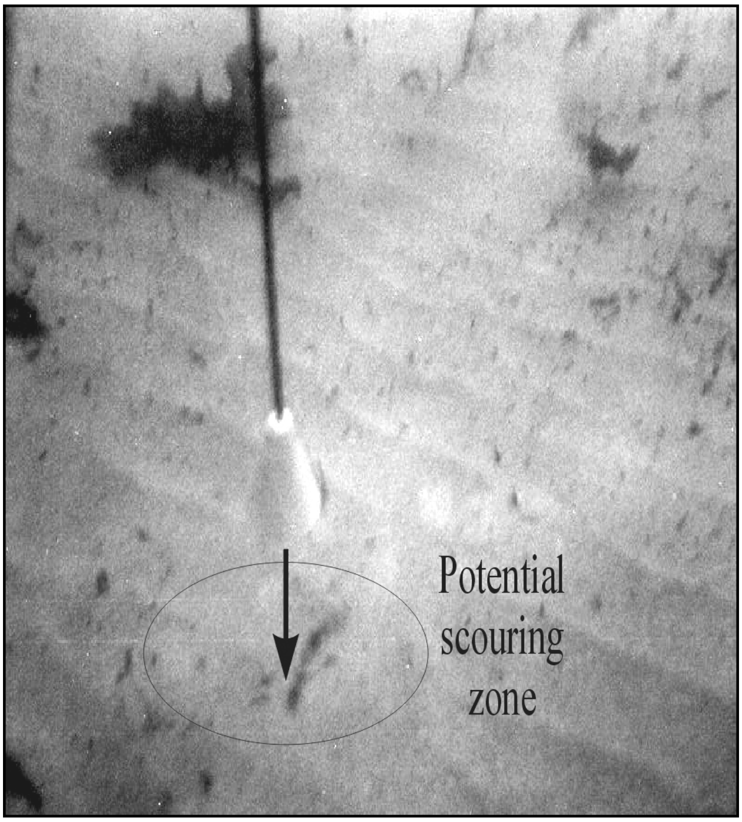

Figure 4. Under water dive image of the instrument when working. Note that there was no noted scouring during the experiment from the presence of the SAM foot.

Standard DOD and Hs assessment

Employing the standard approach of previous studies whereby an assessment of total DOD and average significant wave height are compared, the 5-hour record in this study was examined. This allows will provide a DOD and wave height relationship to be compared against equation (1) or (2). The time period 15:48:00 to 21:24:00 was taken as the total sample period and the net DOD was noted to be 11.0 cm. The average significant wave height for this same period was calculated at 45.2 cm. Using the relationship between Z_m and H_b in (1) and the latter parameters, the constant was calculated at 0.24 giving a revised form of (1) as:

$$Z_m = 0.24\,H_s \quad \textbf{(3)}$$

This compares favourably with the reflective beach equation (2) where the constant was denoted as 0.27. Comparison of seabed levels before and after the experiment were carried out by measuring in the same location the elevation with respect to a local bench mark. The DGPS survey before and after the run (after 1 tidal event) showed a gross change of 7.8 cm which would have been the total net change registered with traditional methods (plus DOD)

High resolution DOD and Hs assessment

With a more detailed record available than previous studies, data was examined to ascertain when there appeared to be a closer relationship between DOD and wave height during the record.

One of the aims of this investigation, and the reasons behind the development of SAM is to advance our knowledge of the concept of wave penetration and wave height sensitivity to water level. In situ wave records were obtained from SAM and DOBIE for the duration of the experiment (fig. 5). Figure 5 shows that there is a correspondence between an increase of sea-bed levels accompanying increasing water levels and associated wave height. There appears to be a lag between the response of DOD to the establishment of waves that achieve the optimum level of orbital speed that penetrates the water

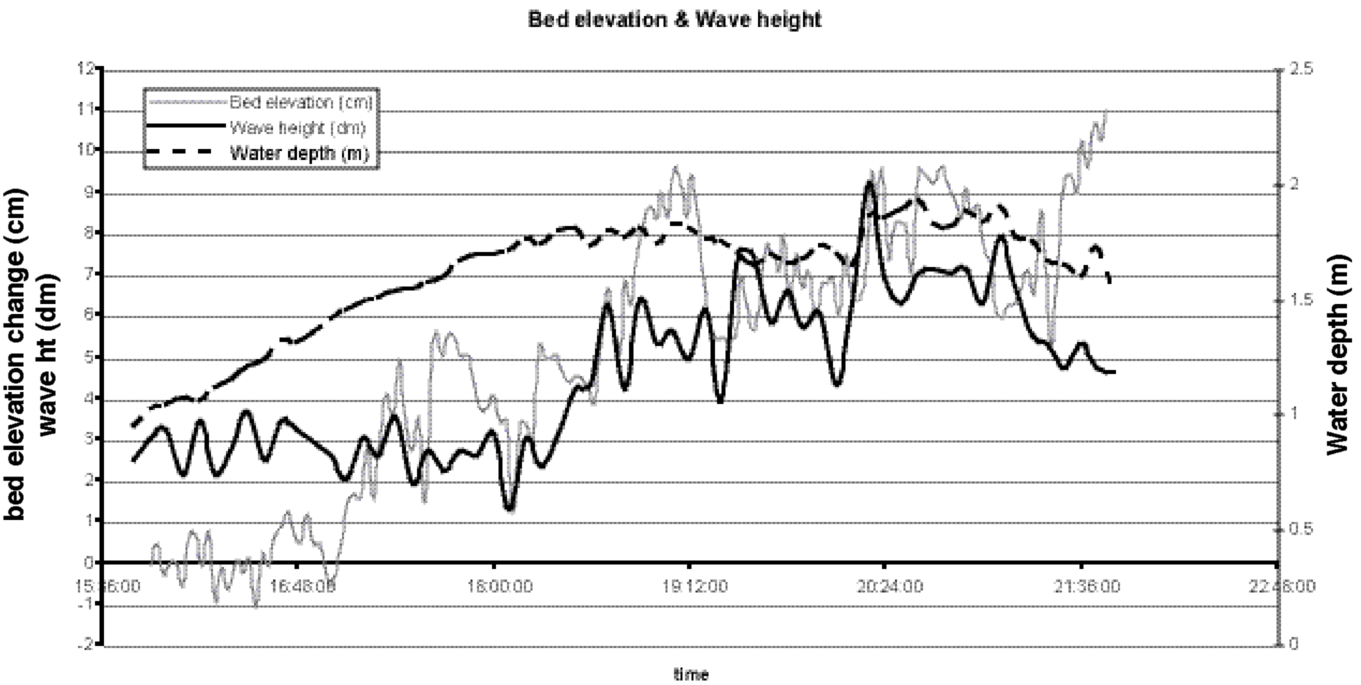

Figure 5. Sample data output (over 5 hrs) from both the SAM and DOBIE wave recorder, showing wave height, water depth and DOD measurements. Note the early lack of relationship between wave heights and DOD at low tide. As the tide increases so does wave heights and this corresponds to a general increase in over all DOD indicating an accretion of sediment on the surface. Deeper water levels appear to show less of a relationship between DOD and wave height possibly due to lack of wave penetration to the sea bed.

column affecting bottom sediment entrainment. At around time 19:00:00 water level is at a maximum and DOD appears to decrease due, possibly, to an excess in water depth that affects optimum wave penetration.

DISCUSSION AND CONCLUSIONS

Previous studies of depth of disturbance in the surf zone have used vertical measurement rods and sediment markers, and therefore only been able to measure effects as integrated over a tidal cycle. It is therefore not clear how the depth of disturbance in sediments in the surf and swash zones depends on the various forcing parameters present in the system. The importance of forcing scales, such as water depth and length scales of the waves and wave groups impacting onto the sediment body need careful consideration in the light of simultaneous measurements of bed elevation changes. The effects of a dynamic beach level cannot consequently be reproduced with confidence in current models of the formation, dynamics and kinematics of the surf zone, and of beach bedload migrations and suspension transports.

Results have shown a remarkable variation in bed elevation changes during the tidal event, particularly when set against the gross variation of only 7.8cm recorded from the DGPS survey. The data has exposed the high degree of bed change activity contained even within one tidal event. The overall bed elevation is trending upward suggesting a depositional event with higher tide and increased wave heights. However, wave height appears to have varying degrees of significance and seems to be controlled by the corresponding tide-driven, water depth available. During the initial stages of the experiment there appears to be little correspondence to wave heights and DOD, with mainly swash activating the surface and relatively lower values of sediment elevation disturbance occurring. With increased water depths of the incoming tide there are increases in wave heights in general, corresponding to much higher DOD levels present. Previous studies (e.g. KRAUS, 1985) have largely over-simplified the relationship of breaker height and depth of disturbance assuming a constant value for the entire tidal period and averaging both DOD and significant wave heights. The initial results from this work show a much more complicated picture of bed elevation events than previously recognised with apparently higher significance between DOD and wave heights occurring at the higher wave heights (up until a point) and water depths.

The potential of examining DOD throughout the tidal cycle at high temporal resolution allows us to focus on the partition of the intervening forces at play and the reacting seabed level. SAM's final design would aim towards addressing a comprehensive analysis of *in situ* measurements for characterisation of morphodynamic systems. In line with ongoing research in a variety of coastal environments, the preliminary investigation reported here identifies that the effect of water level alone can be of significant importance in determining beach states and morphodynamics beyond the established conceptual models of MASSELINK and SHORT (1993), the single-point approaches of GREEN and MACDONALD (2001) or the modelling efforts of MALVAREZ *et al*., (2001). The topic of bed load versus suspended sediment or indeed the debate on prediction of longshore and cross-shore sediment transport is not addressed here. SAM records what is actually occurring on the sea floor in terms of instantaneous deposition or erosion and provides the parameters with which to analyse, in a much more comprehensive way, the relationship between water depth variation, wave action and sediment depth of disturbance in a range of beach environments.

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