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Lagrangian measurements and modelling of fluid advection in the inner surf and swash zones

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ABSTRACT

New laboratory and field data are presented on fluid advection into the swash zone. The data illustrate the region of the inner surf zone from which sediment can be directly advected into the swash zone during a single uprush, which is termed the advection length. Experiments were conducted by particle tracking in a Lagrangian reference frame, and were performed for monochromatic breaking waves, solitary bores, non-breaking solitary waves and field conditions. The advection length is normalised by the run-up length to give an advection ratio, *A*, and different advection ratios are identified on the basis of the experimental data. The data show that fluid enters the swash zone from a region of the inner surf zone that can extend a distance seaward of the bore collapse location that is approximately equal to half of the run-up length. This region is about eight times wider than the region predicted by the classical swash solution of Shen and Meyer [Shen, M.C., Meyer, R.E., 1963. Climb of a bore on a beach. Part 3. Runup. Journal of Fluid Mechanics 16, 113–125], as illustrated by Pritchard and Hogg [Pritchard, D., Hogg, A.J., 2005. On the transport of suspended sediment by a swash event on a plane beach. Coastal Engineering 52, 1–23]. Measured advection ratios for periodic waves show no significant trend with Iribarren number, consistent with self-similarity in typical swash flows. The data are compared to recent characteristic solutions of the non-linear shallow water wave (NLSW) equations and both finite difference and finite volume solutions of the NLSW equations.

The model results are transformed into a Lagrangian reference frame to illustrate particle trajectories, from which advection lengths and particle excursions into and across the swash zone are determined. The particle excursions represent a horizontal mixing length for fluid and sediment and define length scales over which boundary layer growth occurs during run-up. The model results are in excellent overall agreement with the means of the data series. The region defined by the advection length represents the potential effective pickup zone for pre-suspended sediment, and therefore represents an important but diffuse boundary for sediment transport modelling in the inner surf and swash zone.

1. Introduction

Swash zone processes are an important forcing mechanism for sediment transport in the coastal zone and are the principal mechanism for sediment exchange between the surf zone and dune systems. Predicting sediment transport and the resultant morphological change of the beach face remains a challenge and a review of recent progress is given by Masselink and Puleo (2006). Present models for swash sediment transport typically have an Energetics or Shields type model as a core element, where the transport is proportional to the horizontal velocity to some power. However, swash zone flows have significant offshore skewness (Raubenheimer and Guza, 1996; Masselink and Hughes, 1998) which means that present models cannot produce onshore transport and hence cannot predict the accretion of beach berms or equilibrium beach slopes. Consequently, much work has been directed to determine the mechanisms that might balance this offshore bias in the sediment transport predicted by traditional model approaches. Examples include different transport coefficients and friction factors for uprush and backwash transport (Masselink and Hughes, 1998; Cox et al., 2000; Conley and Griffin, 2004), time-varying friction factors (Cowen et al., 2003), infiltration and exfiltration effects (Turner and Masselink, 1998), hindered settling at the high sediment concentrations in the swash (Baldock et al., 2004) and the different influence of turbulence in the uprush and backwash (Puleo et al., 2000; Cowen et al., 2003; Butt et al., 2004; Aagaard and Hughes, 2006). More recently, the role of flow acceleration during the uprush (Puleo and Holland, 2001; Nielsen, 2002; Puleo et al., 2003) has been regarded as important.

The importance of flow acceleration in the uprush has been questioned by Hughes and Baldock (2004) and has been demonstrated to be directed offshore rather than onshore for almost the full extent of the swash zone at all times in the swash cycle (Baldock and Hughes, 2006). Recent state of the art numerical modelling now supports this view (Puleo et al., 2007). Nevertheless, the bed shear stress tends to be

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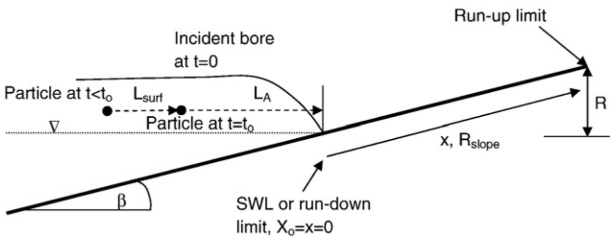

Fig. 1. Definition sketch for run-up, R, and advection length, L_A, on a beach with gradient β. The incident bore reaches the SWL or run-down point at $t=t_o=0$, at which time the bore collapse and swash uprush starts. The advection length, L_A, is the maximum distance seaward of the SWL for which particles starting a distance L_A from the shore at $t=t_o$ just enter the swash zone, $x>0$, during the uprush. The length L_{Surf} is the shoreward particle excursion prior to the start of the uprush. The total advection length, L_{Total}, is given by L_A+L_{surf}. The advection ratio A_{swash} is L_A/R_{slope} and the total advection ratio is A_{Total}/R_{slope}. The surf zone advection ratio, A_{Surf}, is defined as L_{Surf}/R_{slope}.

greater in the uprush than in the backwash (Cox et al., 2000; Cowen et al., 2003; Conley and Griffin, 2004). Indeed, recent direct bed shear stress measurements with a shear plate show that the maximum uprush shear stress occurs at the leading edge of the swash and may be up to four times the maximum backwash stress (Barnes and Baldock, 2007). This higher shear stress is likely to lead to greater bed load transport, an increase in sediment pickup and an increase in the quantity of suspended sediment entrained within the uprush. While this increase can help explain net shoreward transport, additional pre-suspended sediment is advected into the swash zone from the inner surf zone, which has also been considered important in determining the net sediment transport pattern in the swash (Hughes et al., 1997; Alsina et al., 2005; Pritchard and Hogg, 2005; Masselink and Russell, 2006).

Pritchard and Hogg (2005) demonstrated the importance of the advection of pre-suspended sediment in controlling the suspended sediment transport pattern in the swash. In particular, the quantity of sediment entering the swash from the inner surf zone appears a controlling factor in determining both the transport pattern and whether the erosion or accretion occurs. However, the Shen and Meyer (1963), henceforth SM63, swash solution adopted by Pritchard and Hogg (2005), henceforth PH05, leads to unrealistically small swash depths and, consequently, minimal sediment transport and morphological change in the upper half of the swash. Jackson et al. (2004) considered the advection of sediment within the swash zone using a shallow water numerical model, and included a diffusion model to describe how the sediment concentration varied with time. However, they considered all sediment to be advected at the velocity of the leading edge of the swash, which potentially leads to considerable errors in the lower swash zone. Hughes et al. (2007) mapped the spatial and temporal variation in sediment concentration across the swash zone, and illustrated the importance of the pre-suspended sediment load during the uprush.

Alsina et al. (2005) developed a Lagrangian model for swash sediment transport that included bed load, a time-varying concentration of pre-suspended sediment at the swash boundary and pickup of sediment within the swash zone, and could predict onshore transport with a standard sediment transport coefficient in the Shields type bed load model. The relative magnitude of the pre-suspended sediment transport compared to the pickup of sediment within the swash zone was shown to be important in controlling the location of the maximum shoreward transport. This position represents a pivot point on the beach and Weir et al. (2006) show that the morphodynamics of beach berms are governed to a large extent by the presence of a pivot point in the cross-shore transport.

Using the SM63 swash solution, PH05 suggested that sediment is advected into the swash zone from a very narrow region of the inner surf zone, extending 1/16th of the run-up length seaward of the location of bore collapse (the start of the run-up) (see Fig. 7a below). This value is very small, and unduly limits the volume of water and sediment that is predicted to enter the swash. More recently, Guard and Baldock (2007) showed that the SM63 analytical swash solution is unrealistic, since the boundary conditions for the solution are not representative of real swash. New characteristic solutions presented by Guard and Baldock (2007) give much greater inflow into the swash, greater flow depths and later flow reversal. These differences imply that much greater quantities of fluid and sediment enter the swash zone than would be predicted by the SM63 and Pritchard and Hogg solutions. Masselink and Puleo (2006) note that such sediment advection from the surf zone into the swash zone plays a key role in controlling the sediment transport but has hardly received any attention in the laboratory or field.

This paper addresses this point and presents Lagrangian laboratory and field data illustrating fluid advection into the swash zone, and that to our knowledge are unique. The experiments illustrate the potential sediment advection into the swash zone and demonstrate the importance of the surf–swash interaction on swash hydrodynamics and sediment transport. The data are compared to the Guard and Baldock (2007) swash solutions and two numerical non-linear shallow water wave models, working in a Lagrangian reference frame to illustrate particle trajectories. Section 2 of the paper describes the advection experiments that define the length of the inner surf zone region from which sediment can be advected into the swash. The experimental results are presented in Section 3. Section 4 compares that experimental data to the model predictions, with additional discussion of particle trajectories within the swash. Final conclusions follow in Section 5.

2. Experimental setup

The advection length is the maximum distance seaward of the swash boundary from which a fluid particle can enter the swash zone (cross the swash boundary), and is illustrated in Figs. 1 and 2. For real conditions, the swash boundary is the run-down limit (which varies extensively across the beach face, see Hughes and Moseley (2007)), but for single swash solutions or bores propagating into still water, the boundary is the still water line (SWL) on the beach. The SM63 swash solution used by PH05 to illustrate the advection length corresponds to the boundary conditions for a stationary dam-break flow on a sloping beach. Consequently, the fluid seaward of the still water line is not moving before the swash starts, $t=t_o=0$, and the advection length represents the excursion of a particle that starts to move landward only when the uprush starts. Hence, to be consistent with PH05, we define the advection length L_A such that it represents the particle excursion after $t=t_o=0$. However, under incident waves and bores, fluid particles are moving shoreward before the swash starts at $t=t_o=0$, and the

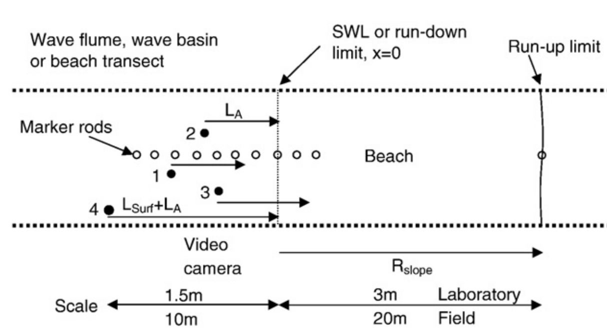

Fig. 2. Schematic of measurement technique. Marker rod (o) spacing 0.05 m in laboratory, 1–0.5 m in the field. Almost neutrally buoyant particles (●) are released to enter the water behind the bore front at $t=t_o$. Particle 1 does not enter the swash. Particle 3 is released too far landward. Particle 2 just reaches the SWL or run-down limit, and gives the advection length L_A. For single solitary bores, particle 4 gives both the advection length before $t=t_o$, L_{surf}, and the total advection length, L_{Total}.