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Large-scale experiments on beach profile evolution and surf and swash zone sediment transport induced by long waves, wave groups and random waves

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ABSTRACT

New large-scale laboratory data are presented on the influence of long waves, bichromatic wave groups and random waves on sediment transport in the surf and swash zones. Physical model testing was performed in the large-scale CIEM wave flume at UPC, Barcelona, as part of the SUSCO (swash zone response under grouping storm conditions) experiment in the Hydralab III program (Vicinanza et al., 2010). Fourteen different wave conditions were used, encompassing monochromatic waves, bichromatic wave groups and random waves. The experiments were designed specifically to compare variations in beach profile evolution between monochromatic waves and unsteady waves with the same mean energy flux. Each test commenced with approximately the same initial profile. The monochromatic conditions were perturbed with free long waves, and then subsequently substituted with bichromatic wave groups with different bandwidth and with random waves with varying groupiness. Beach profile measurements were made at half-hourly and hourly intervals, from which net cross-shore transport rates were calculated for the different wave conditions. Pairs of experiments with slightly different bandwidth or wave grouping show very similar net cross-shore sediment transport patterns, giving high confidence to the data set. Consistent with recent small-scale experiments, the data clearly show that in comparison to monochromatic conditions the bichromatic wave groups reduce onshore transport during accretive conditions and increase offshore transport during erosive conditions. The random waves have a similar influence to the bichromatic wave groups, promoting offshore transport, in comparison to the monochromatic conditions. The data also indicate that the free long waves promote onshore transport, but the conclusions are more tentative as a result of a few errors in the test schedule and modifications to the setup which reduced testing time. The experiments suggest that the inclusion of long wave and wave group sediment transport is important for improved near-shore morphological modeling of cross-shore beach profile evolution, and they provide a very comprehensive and controlled series of tests for evaluating numerical models. It is suggested that the large change in the beach response between monochromatic conditions and wave group conditions is a result of the increased significant and maximum wave heights in the wave groups, as much as the presence of the forced and free long waves induced by the groupiness. The equilibrium state model concept can provide a heuristic explanation of the influence of the wave groups on the bulk beach profile response if their effective relative fall velocity is larger than that of monochromatic waves with the same incident energy flux.

1. Introduction

Long waves have been proposed to be important for coastal zone sediment transport for many years (Carter et al., 1973; Short, 1975; Bowen, 1980; Holman and Bowen, 1982; Roelvink and Stive, 1989; O'Hare and Huntley, 1994). Although most gross sediment transport is induced by short-scale wind and swell waves, the morphological evolution depends on the gradients in the sediment transport, and these can be subtly changed over the time-scales of long waves and wave groups. In addition, the groups introduce further unsteadiness and intermittency into the short-wave sediment transport processes, with the potential to change relationships between sediment pick-up, suspension and settling and hence net sediment transport rates and direction. Recent work has suggested that while long time-scale beach evolution is strongly controlled by preceding conditions and displays consistent behaviour patterns, the evolution is still deterministic (Ruessink and Kuriyama, 2008), and that improved parameterisation of larger scale sediment transport processes is required, since the time-averaging in broad-scale models necessarily excludes long waves and wave groups. However, direct experimental investigation

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of the role of long waves and wave groups has been limited and, in the field, relies on correlating morphological and long-wave length scales (e.g. Aagaard, 1990; Aagaard et al., 1994). However, because of hydrodynamic feedback between the morphology and long waves, the long-wave structure may be determined by the morphology, as proposed by Symonds and Bowen (1984) and as observed by Michallet et al. (2007), rather than the other way around. Therefore, it is difficult to identify the influence of the long waves on the morphology without a direct comparison between conditions with and without long waves. Over broader time and space scales, this morphological–hydrodynamic feedback becomes particularly important (Plant et al., 2004; Brocchini and Baldock, 2008).

The direct influence of long waves on sediment transport directions is complicated and varies across the near-shore zone. Offshore of the breakpoint, the expectation is that the bound long waves associated with wave groups will promote offshore transport (Shi and Larsen, 1984; Deigaard et al., 1999). Local suspended sediment transport measurements tend to support this model (Osborne and Greenwood, 1992; Aagaard and Greenwood 2008). Onshore of the bar, no clear model exists, but long-wave transport tends to be predominantly landward. Aagaard and Greenwood (2008) proposed that long waves advect sediment away from maxima in the relative incident wave height (H/d), which typically occur near the crests of longshore bars, except very close to the shoreline where a monotonic increase in relative incident wave height is observed (Power et al., 2010). This implies divergence of infragravity sediment transport at wave breakpoints (bars), which should cause destruction of the bar crest or the landward migration of the bar crest. This mechanism also offers an explanation for the very large range of observed magnitudes in long-wave sediment transport, and also for the observed divergent transport directions. Offshore of the surf zone and in the outer surf zone, Ruessink et al. (1998) noted that long-wave sediment transport was generally offshore, but an order of magnitude smaller than the transport by short waves and undertow, although these tend to cancel out near the breakpoint. Ruessink et al. (1998) also noted that the transport induced by free long waves did not appear to be significant around the outer breaker zone.

Wave groups also influence the short-wave transport, as shown by Sato (1992). In this case, the inverse relationship between the direction of maximum flow velocity and the direction of suspended sediment transport over rippled beds can lead to onshore sediment transport at short-wave frequencies, but offshore transport at long-wave frequencies. Sato (1992) also noted that sediment concentrations were higher under grouped waves than for monochromatic waves with the same overall energy flux. The turbulence production and dissipation that are partially responsible for generating and maintaining sediment suspensions are also influenced by the mode of breaking, which varies for different wave steepness and for different waves within the wave groups (Ting and Kirby, 1995; Ting, 2002). This further complicates the influence of wave groups.

The importance of long waves is not only the additional wave induced velocity and the long-wave influence on the short-wave hydrodynamics (Goda, 1975; Baldock and O'Hare, 2004) but also larger scale processes, such as the formation of standing waves, or a cross-shore and longshore nodal structure both inside and outside the surf zone (e.g. Holman and Bowen, 1982; Symonds and Bowen, 1984). Dally (1987) investigated experimentally if the formation of longshore bars was consistent with the surf beat structure, yet very little evidence for surf beat contributing to the bar formation was observed, and undertow appeared the dominant bar forming mechanism. Numerical modeling (Roelvink and Stive, 1989; Roelvink, 1993) has been used to investigate the role of surf beat by including and excluding long-wave terms from a numerical model and comparing the predicted morphology with a measured beach profile from random wave tests. Including long waves in the model smoothed the bar, reduced the bar height and moved the bar crest seaward, and also produced less erosion in the inner surf zone. Jannat and Asano (2007) adapted a numerical model from Kobayashi et al. (1987) to investigate sediment transport under long waves. The long waves induced small changes in the surf zone, and larger changes in the swash zone, where long waves have maximum amplitude.

An alternative macro-scale approach to forecasting beach profile evolution derives from the heuristic model based on the relative fall velocity parameter, $\Omega = H/w_sT$, developed by Gourlay (1968) and Dean (1973). This bulk-response approach has since been adopted in more complex form through equilibrium state or relaxation models. These models have been used to describe the types of beach states, evolution of beach states, shoreline movement and sand bar behaviour by numerous authors, using either Ω or other measures of wave energy (Sunamara, 1984; Wright et al, 1985; Larson and Kraus, 1989; Dalrymple, 1992; Plant et al., 1999, Miller and Dean, 2004; Yates et al., 2009). While the success of these bulk-response models for delineating short and long term periods of erosion or accretion in field conditions has been mixed, there is a strong inheritance from antecedent conditions which influences the correlation between the observed parameter and instantaneous Ω, as does the response time of the system (Wright et al., 1985). Very recently, Yates et al. (2009) have shown that, for the same beach, i.e. constant w_s, either wave energy or Ω discriminate well between erosive and accretive events if the antecedent beach width is accounted for. This form of model appears to be a more robust predictor of beach response for laboratory conditions (Hattori and Kawamata, 1980; Sunamara, 1984; Dalrymple, 1992). In part, this is probably because of the reduced complexity of the forcing, "steady" wave and water level conditions and measurement accuracy. However, in such experiments, the initial beach profiles are usually the same or very similar for all wave conditions. Therefore, the absence of the influence of antecedent beach conditions is very likely to be the key reason why such models perform better for laboratory conditions. Further, since the laboratory tests typically commence with an initially planar profile, the evolution of the profile to either a bar (erosion) or berm (accretion) profile is a clear indicator of the direction of the total net sediment transport (e.g. Fig. 4 of Dalrymple, 1992). Hence, if Ω describes the profile response from plane conditions, it will also provide a good estimate of the transport direction and whether erosive or accretive conditions dominate. This heuristic approach is adopted later to consider the influence of perturbing monochromatic conditions with free long waves and wave groups.

Both free and forced long waves occur in the near-shore zone and surf zone, which may be perpendicular to the shore (leaky waves) or edge waves (trapped alongshore), but little previous work has considered the overall impact of free long waves on the beach evolution. Similarly, direct investigation of how long waves and wave groups modify sediment transport and the erosion or accretion of beaches is lacking. For example, while it is well known that irregular waves (sea waves) tend to promote erosion but more regular waves (swell waves) tend to promote recovery, it is not clear if this is related to changes in energy or to changes in irregularity or groupiness. Seiching during small-scale beach morphology experiments with random wave conditions was observed by Dally (1991) to influence the final equilibrium profile, smooth the bar-trough morphology and carry sediment higher in the swash zone. Baldock et al. (2010) performed small-scale beach morphology experiments to investigate directly the overall role of shore normal surf beat on sediment transport. Baldock et al. (2010) considered specific combinations of short waves and long waves, and a series of bichromatic wave groups, and compared the beach evolution to that induced by monochromatic waves in isolation, but did not consider random waves. The experiments indicated that free long waves tended to promote shoreward transport, or accretion, while the bichromatic wave groups increased offshore transport and promoted erosion. However, the small-scale of the experiments (water depth 0.5 m, wave height