Megaripple dynamics on a dissipative sandy beach

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ABSTRACT

Miles, J., Thorpe, A., Russell, P., Masselink, G., 2014. Megaripple dynamics on a dissipative sandy beach. *In:* Green, A.N. and Cooper, J.A.G. (eds.), *Proceedings 13th International Coastal Symposium* (Durban, South Africa), *Journal of Coastal Research*, Special Issue No. 70, pp. 187 – 192, ISSN 0749-0208. DOI:10.2112/SI70-032.1

Conventional forced models of bedform dimensions link bedform wavelength and height to wave orbital excursion and wave orbital velocity. Self-organization models, however, suggest that bedform wavelengths either grow, remain stable, or are wiped flat, but are unable to reduce in length. This paper presents measurements of megaripple evolution on a macrotidal sandy dissipative beach at Perranporth, England, using measurements from a Sand Ripple Profiler. Measurements were made as the tide flooded and ebbed over the instruments, giving a cross-section of the moving surf zone for 12 separate tides. Water depths varied from 1 to 6 m, and wave heights were up to 2.2 m. The data allowed megaripple dimensions to be observed with heights up to 30 cm and wavelengths up to 1.8 m.

Megaripples were observed to grow *and* decay in both length and height. Megaripple spacing did not increase consistently with age of ripple. Megaripple lengths changed at rates of up to 5 cm/minute, and height changed at rates of up to 0.5 cm/minute. Maximum changes took place in large orbital velocity conditions. At orbital velocities > 0.5 m/s, ripples attempted to stabilize at a wavelength related to the orbital excursion, suggesting a forced mode. The most stable ripples had the greatest height and steepness. At orbital velocities < 0.5 m/s the spacing was greater than the orbital excursion, suggesting self-organized growth may be a more appropriate model for small orbital velocities.

ADDITIONAL INDEX WORDS: *megaripples, self-organization, surf zone, bedforms, dissipative beach.*

INTRODUCTION

Bedforms develop on the seabed in sandy nearshore environments, and make an important contribution to bottom boundary layer hydrodynamics and sediment transport (Fredsoe and Deigaard, 1992). Bedforms take on a variety of length scales, including wave ripples, megaripples and sandbars. Megaripples are particularly important in the surf zone, as they are reasonably ubiquitous features (Clarke and Werner, 2004) and make an important contribution to the overall bed roughness (Gallagher *et al*., 2003). Megaripples typically have heights of ~0.5 m and wavelengths of 1 to 5 m (Gallagher *et al*., 1998).

Nielsen (1992) identified that wavelength and height of ripples increase as a function of orbital excursion and mobility number through empirical modeling of laboratory tests. However, field measurements of megaripple spacing in a saturated surf zone suggest that bedform spacings (i.e. wavelengths) are not solely dependent on forcing and are not well represented by these empirical models (Gallagher, 2003). Video observations of megaripples on a natural beach suggest that megaripple spacing increases with time (Clarke and Werner, 2004). Their results suggest that spacing growth is approximately linear for low age (0.01 days to 0.5 days) and is logarithmic beyond this. The scatter in the age/spacing relationship was large, but the bed state was uncorrelated with offshore wave height, period or direction.

Self-organization based models have provided a mechanism for wavelength growth, and are able to predict both stable wavelengths and replicate growth characteristics (Coco and Murray, 2007; Gallagher, 2011). Gallagher (2011) modeled self-organized megaripples in the nearshore and found that the self-organisation model of bedform spacing leads to the prediction that the megaripples will grow continually. The predictive curve takes a similar form to that of Clarke and Werner (2004). Werner and Kocurek (1999) modeled the evolution of bedform patterns for linear and oscillatory flows using defect dynamics and identified that for dunes in a linear flow their spacing increased with time. For oscillating flows in constrained channels, the ripple spacing was a function of the near-bed orbital excursion, with wavelength $\lambda = 0.65$ D, where D is the orbital excursion.

When hydrodynamic conditions change, it has been shown that there is potential for ripples to be no longer in equilibrium with forcing hydrodynamic conditions (Austin *et al.,* 2007) and that it takes a certain amount of time for the ripples to respond. This is also the case for megaripples and is a particular problem for macro-tidal beaches, which may experience relatively rapid changes of conditions as the tide floods or ebbs, and the wave height and position in the surf zone change. If the self-organization model is appropriate, the megaripples should grow when conditions are favorable, remain stable if the hydrodynamic conditions (mobility number) are too weak, or become washed flat if conditions become too energetic. In this paper, therefore, we look at observations of the growth rates of megaripples, in order to

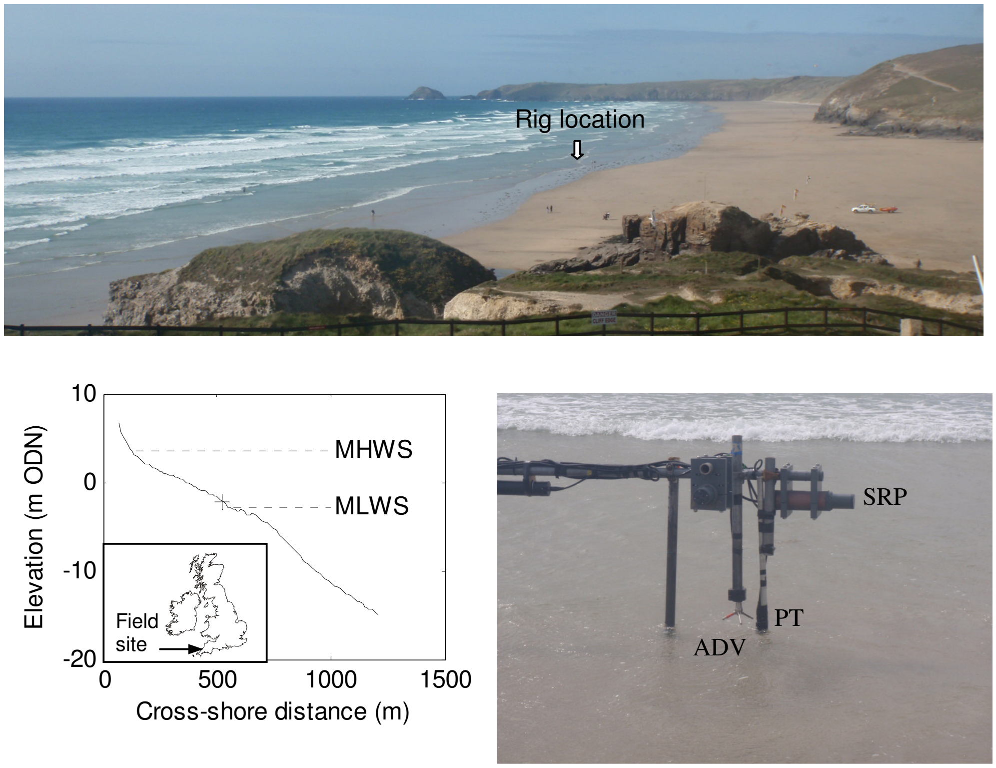

Figure 1. The field site at Perranporth (top), with approximate rig position indicated. The beach profile for the experiment period (bottom left) indicates the deployment location (+) relative to the position of Mean High Water Springs and Mean Low Water Springs (ODN refers to Ordnance Datum Newlyn, which is the approximate UK mean sea level datum). Instrumentation (bottom right) comprised a Sand Ripple Profiler (SRP), an Acoustic Doppler Velocimeter (ADV) and a Pressure Transducer (PT).

ascertain if they do indeed grow in length until flattened, or if they are capable of reducing in size.

FIELD MEASUREMENTS

Field measurements were made at a high energy, macrotidal dissipative sandy beach at Perranporth (North Cornwall, UK) (Figure 1). Two separate field deployments were carried out in May 2011 and October 2011, each for six separate high tides. The tides described in this paper are identified as tides 11 - 16 and 21 - 26, representing the May and October deployments, respectively.

Perranporth has a mean tidal range of 6.1 m, and a mean offshore wave height of 1.6 m (Davidson *et al.,* 1997). Sediments at the site are medium sand (D_{50} = 0.28 mm). The beach profile was reasonably linear, with an average slope of 1/80.

Measurements were made by deploying an instrumented rig near the low water mark, roughly between the spring and neap low tide level. The instruments logged data as the tide flooded and ebbed over the rig, and this allowed measurements to be made in a variety of water depths from 1 to 6 m, and in a variety of wave/current conditions in the surf and shoaling zones.

A Sand Ripple Profiler (SRP) measured a line scan of seafloor elevation. The SRP was positioned 90 cm above the bed, and measured a 2-m on-offshore line once per minute. Data was post-processed to give regular horizontal (on-offshore) spacing between points of ~1 cm over the 2-m footprint of the scanner. Flow velocities were measured using an Acoustic Doppler Velocity meter (ADV) with a sensing volume 25 cm above the bed. Mean water depths and wave heights were measured using a Pressure Transducer (PT) deployed at bed level. Hydrodynamic data were recorded at 16 Hz for tides 11 - 16 and 8 Hz for tides 21 - 26. Data from the SRP, ADV and PT were divided into 10-minute runs for processing. Only hydrodynamic data were considered for runs when bedform data from the SRP was available. This limited the data set to water depths greater than 1 m, because only then was the SRP covered by water sufficiently to yield continuous information on the seabed topography.

HYDRODYNAMICS

Hydrodynamic conditions for each of the tides recorded at the rig are shown in Figure 2. Each 'run' represents a 10-minute

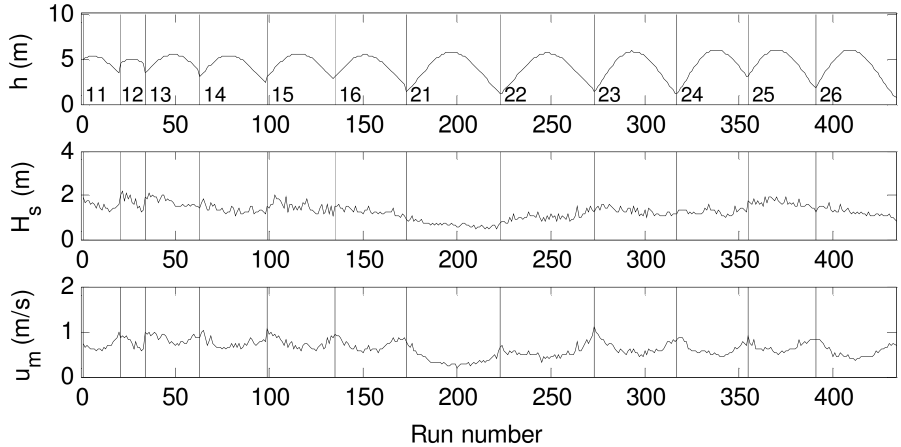

Figure 2. Hydrodynamic data: water depth h, wave height H_s and orbital velocity u_m. Each 'Run' represents a 10-minute section of data. Vertical lines indicate when instruments were dry at low tide or between deployments.

section of data. The run numbers start when data collection started on the first tide. The instruments were dry at low water and between experiments, and these time periods with no data have been removed. Average water depths (h) were calculated for each run, allowing for offsets of instrument heights and atmospheric pressure. Significant wave heights (H_s) were calculated with a correction for depth attenuation, and were in the range H_s = 0.48 - 2.19 m. Wave periods ($T_{1/3}$) indicate mostly swell waves for the measured tides, with $T_{1/3}$ = 10 - 11 s, although data were also collected for $T_{1/3}$ = 7 - 8 s (tides 25 and 26). The wave orbital velocity was calculated as $u_m = 2\sqrt{\sigma^2_u}$ (where σ^2_u is the cross-shore velocity variance) following Masselink *et al.* (2007).

BEDFORMS

Sequential profiles from the SRP were time-stacked and are displayed as an image plot to illustrate different features of interest (Figure 3). Megaripples migrated shoreward for the majority of the time (Miles *et al.,* 2013), i.e., crests move down the image as time passes. In terms of ripple wavelength, the plots show that there are instances where (a) megaripples increase in wavelength (e.g., latter part of tide 25) and (b) reduce in wavelength (e.g., tide 11).

Crawford and Hay (2001) identified that the heights of wave ripples and megaripples could be determined directly from the variance of the bed-level trace as $\eta = \sqrt{(8\ (\sigma^2(z)))}$. To separate out the megaripple component, each bedform scan was first low-pass filtered below a cut-off of 35 cm to remove wave ripples and reduce noise. The Crawford and Hay (2001) calculation was carried out on the filtered elevation data, to give megaripple heights.

Megaripple wavelengths were calculated from an autocorrelation of the scan, to identify the distance from crest to trough (Masselink *et al.,* 2007). The wavelength was quantified as twice the spatial lag corresponding to the strongest negative auto-correlation peak. The maximum value was limited by the requirement for at least half a wavelength to be visible in the scan.

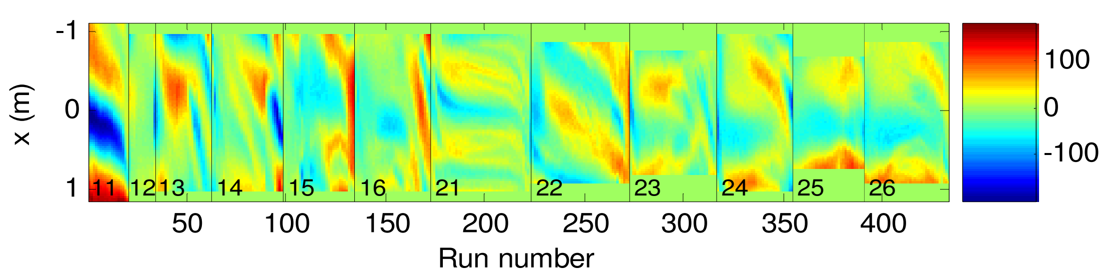

Figure 3. Timestacks of bedforms measured by the SRP. Colourscale indicates vertical relief with +ve (-ve) values in red (blue) and a vertical scale of mm. The SRP is fixed at 'x = 0', and the shore is towards the base of the plot. Data are shown for one scan per minute. Run numbers shown are synchronous with hydrodynamic data and 1 run = 10 minutes. On-offshore data resolution is 1 point per cm. Vertical lines indicate the gaps when the instruments were dry after/before each tide or between deployments.

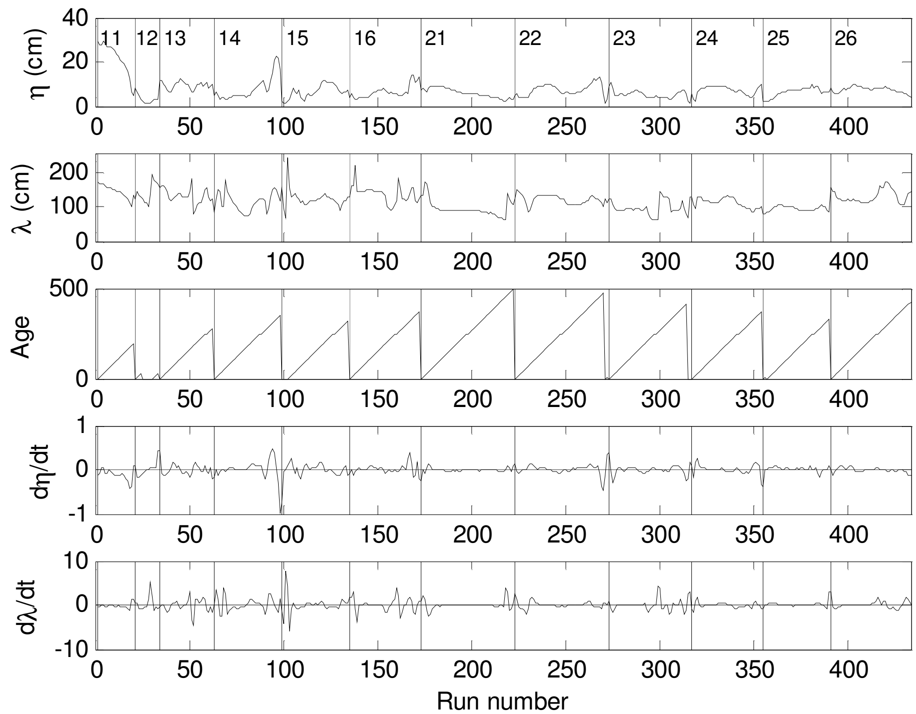

Figure 4. Bedform parameters: height η and wavelength λ of megaripples. The age of the megaripples is the time since the bed was last flat (minutes). Rates of change of height (dη/dt) and wavelength (dλ/dt) have units of cm/minute.

Megaripple age was quantified for each run as the length of time since either (a) the bed was last flat, or (b) since the bed had last been dry at low tide or between experiments. A 'flat' bed was determined as when the bedform height was < 2 cm. In reality, a flat bed was rare, so the general 'age' statistic for this position in the intertidal is most dependent on the time since the last dry period at low tide. Megaripple ages therefore reach a maximum of ~ 500 minutes at this location due to the semi-diurnal tide.

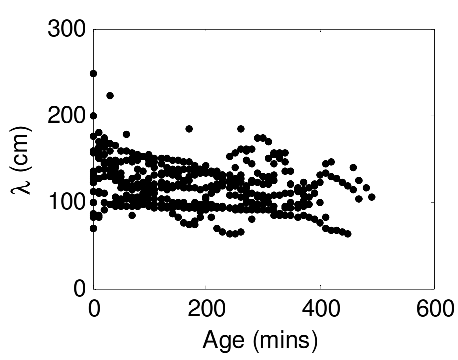

Figure 5. Wavelength of bedforms (λ) as a function of age, timed from either the previous flattening or from the first measurement after the previous low tide.

Megaripples ranged in height from flat bed to 30 cm (Figure 4). They were > 10 cm for 13.4% of the time, and were greater than 6.6 cm high for 50% of the time. Megaripple wavelengths were typically in the range 1 to 2 m. When megaripple heights were > 6.6 cm (i.e. the highest 50% of megaripples), the average megaripple wavelength was 1.25 m. Both growth and decay of elevation and wavelength are evident. The changes, in general, appear to happen towards the start and end of the tides, when water is most shallow and orbital velocities are largest.

Megaripple wavelength is plotted against megaripple age in Figure 5. Examining the sequences of data points in the plot, it is possible to identify sets of data where the spacing is both increasing and decreasing. Despite large scatter in the data, there is some evidence that the megaripples reduce in size over the time of a tide. The average reduction in spacing is 3.5 cm/hr, but the r-squared is low (0.075).

The rate of change of megaripple morphology (height and wavelength) is related to the orbital velocity (Figure 6). The most rapid changes appear to occur when the orbital velocity is largest. Changes of both wavelength and height can be positive (up to 5 cm/min) or negative (5 cm/min), suggesting that the rates of growth and decay are broadly similar. However, a large orbital velocity does not necessarily mean that wavelength change will take place, and in many instances no change takes place when the

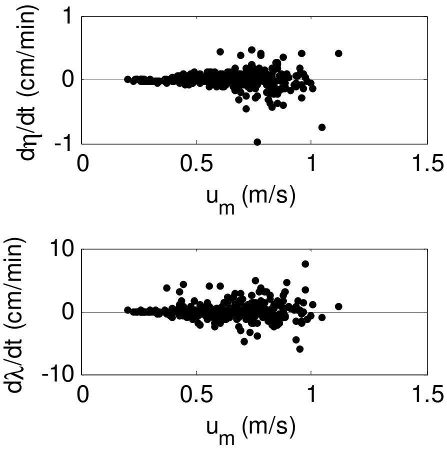

Figure 6. Rate of change of megaripple height (dη/dt) and megaripple wavelength (dλ/dt) (from SRP data) plotted against orbital velocity (u_m) (from ADV data). Positive (negative) values indicate growth (decay) of the megaripples.

orbital velocity is large. This may occur because the ripples are in equilibrium with the hydrodynamic forcing.

The rates of wavelength change, may be considered in terms of the megaripple height and steepness (Figure 7). The fastest changes in wavelength (positive and negative) happen when the megaripple height is smallest (< 10 cm). Rates are least when the ripple height and steepness is largest. This suggests that as the megaripples grow in height and become steeper, a stable condition is gradually reached.

There is evidence that the megaripple wavelengths are attempting to match the conditions dictated by forcing hydrodynamics (Figure 8). Wavelength broadly increases with both wave semi-orbital excursion (calculated as $A_o = u_m T/2\pi$

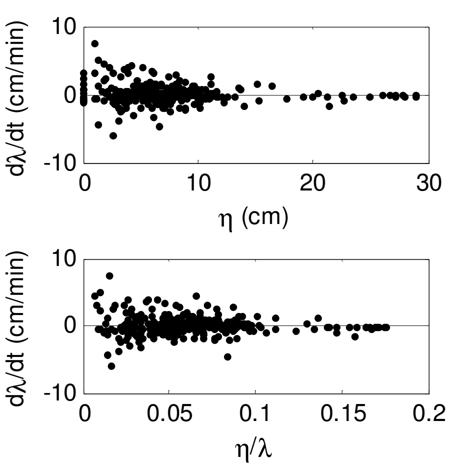

Figure 7. Rate of change of megaripple wavelength (dλ/dt) plotted against megaripple height (η) and steepness (η/λ).

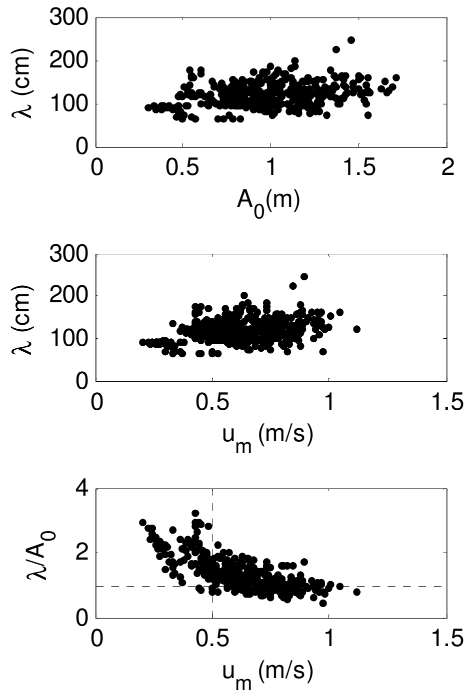

Figure 8. Megaripple wavelength (λ) as a function of orbital semi-excursion (A_0) and orbital velocity (u_m). λ/A_0 is a normalised excursion, frequently used in predictive models of bedform wavelength. As u_m increases, λ/A_0 stabilises at ~ 0.95.

following Soulsby (1997)) and with orbital velocity, but the scatter is large. At low values of u_m (< 0.5 m/s), the normalised wavelength λ/A_o increases with reducing u_m. As u_m increases, λ/A_o appears to stabilise at a value of roughly 0.95. The implication of this is that as the orbital velocity increases, the bedform spacing becomes more constrained by the orbital velocity. An approximate cut off value between the two regimes appears to exist at u_m = 0.5 m/s.

DISCUSSION

The data presented here are limited to a relatively narrow on-offshore scan length (~ 2 m), and only one on-offshore line was possible (spatially). Measured and quantified information on the orientation of the ripples and on the three-dimensional patterns is therefore not available. Low tide wading observations suggest that the ripple crests were reasonably shore parallel and were approximately constant in the alongshore direction for distances of several meters. The adjacent crests and troughs evident in the SRP data are therefore taken as a reasonable indication of megaripple wavelength.

It is possible that the bedforms are responding to mean flows as well as orbital velocities. The orientation of the megaripples indicates that these are responding to on-offshore flows, rather than longshore flows. The magnitude of the oscillatory on-offshore flows is large (up to 1 m/s) compared to the mean flow (up to 0.3 m/s). The influence of these different parameters is difficult to separate in the surf zone, because the strongest offshore flows (e.g., undertow) occur at the same time as the largest orbital velocity. In this investigation, the magnitude of the mean cross-shore flow was small compared to the orbital velocity, and the orbital flow was assumed to be the most important hydrodynamic variable driving wavelength change.

Austin *et al.* (2007) identified that a lag can occur between the forcing hydrodynamics and the bed response. The large tidal range at this site means that putting the ripple age concept into context is complex, because the water depth and flow velocity conditions vary as the tide floods and ebbs over the sensors. However, the results do indicate that there is a reduction in the rate that bedforms change shape as they become more developed (i.e., rates of wavelength change reduce as the ripples become higher and steeper). Any lags between flow conditions and bedform will therefore be short lived during the early developmental phases, but exacerbated when bed features are well developed.

Self-organisation models (e.g., Gallagher *et al.,* 2011) suggest that megaripple spacing grows in time under oscillatory flow conditions, but that the bed will either not change if a threshold shear stress is not passed, or be flattened if the flow strengths are too strong. The self-organisation approach offers an interesting solution to the observations of Clarke and Werner (2004), who identified meagripple spacing increasing with ripple age. The rates of growth and decay of megaripple spacing identified here are ~5 cm per minute. These growth rates are similar to those reported by Clarke and Werner (2004) for newly developing ripples. Their predictive curve suggests growth rates of 5 cm/minute for ripple age of 21 minutes, 0.28 cm / minute for ripple age of 0.5 days (720 minutes). The main difference identified here is that the ripples appear to decay as well as grow.

Werner and Kocurek (1999) indicate that the wavelength of dunes in unidirectional flows increase with age, but that for reversing flows the wavelength is related to the orbital excursion (D), and may be approximated by $\lambda = 0.65$ D (equivalent to $\lambda/A_0 = 1.3$ in this data) for small λ. In the present contribution, when orbital velocities are large, the value of λ/A_0 appears to reach a minimum of ~0.5 (i.e. $\lambda = 0.25$ D), and stabilises at approximately 0.95 (i.e. $\lambda = 0.475$ D), suggesting that the forced model may be appropriate at high orbital velocities. For smaller orbital velocities, the value of λ/A_0 is larger, and increases as the orbital velocity reduces. The wavelengths are over-sized for a given orbital excursion, possibly indicating self-organised growth is dominating over the forced relationship with A_o. It is possible that an evolved self-organization model, or a combined forced / self-organized model may cope with the differences and offer a more consistent predictor for ripple behavior than the existing individual approaches.

CONCLUSION

Megaripples were observed to grow and decay in both length and height. Megaripple spacing did not increase consistently with age of ripple. Megaripple lengths changed at rates of up to 5 cm/minute, and height changed at rates of up to 0.5 cm/minute. The greatest changes took place in larger orbital velocity conditions. In high orbital velocity conditions ($u_m > 0.5$ m/s), the ripples attempted to stabilize at a wavelength related to the orbital excursion, suggesting a traditional empirical forced model may be appropriate. In lower orbital velocities ($u_m < 0.5$ m/s), the relative spacing of wavelength to orbital excursion increased, suggesting self-organized growth may be prevalent. The most stable ripples had the greatest height and steepness.

ACKNOWLEDGEMENTS

The fieldwork for this project was funded by a partnership grant from the UK Natural Environment Research Council (NERC) and the UK Royal National Lifeboat Institution (RNLI), ‘Dynamics of Rip Currents and Implications for Beach Safety (DRIBS)’, (NERC ref: NE/H004262/1).

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