



Sand ripples in irregular and changing wave conditions: a review of laboratory and field studies

J.S.Doucette
T.O'Donoghue

University of Aberdeen, Department of Engineering

December 2002

EC MAST Project No. MAS3-CT97-0086



Sand ripples in irregular and changing wave conditions: a review of laboratory and field studies

December 2002

**JEFFREY S. DOUCETTE
TOM O'DONOGHUE**

**DEPARTMENT OF ENGINEERING
UNIVERSITY OF ABERDEEN
KINGS COLLEGE
ABERDEEN, AB24 3UE
SCOTLAND**

Phone: +44 (0) 1224-272806
j.doucette@eng.abdn.ac.uk



SAND RIPPLES IN IRREGULAR AND CHANGING WAVE CONDITIONS: A REVIEW OF LABORATORY AND FIELD STUDIES

1.0 INTRODUCTION

A large number of studies have been carried out on wave-generated ripples since Bagnold's early experiments with oscillating trays of sediment in still water (Bagnold, 1946). They include field studies, laboratory wave tank experiments and oscillatory flow tunnel experiments. Most of the laboratory work has involved regular wave flows and "equilibrium" ripple conditions. Very few laboratory studies have involved *irregular* flows and even fewer have involved irregular flows with periods and amplitudes typical of field conditions (Appendix). In contrast to the laboratory work, field measurements involve irregular flows and, often, non-equilibrium conditions because of the differences in time-scales between flow and bed changes. In non-equilibrium conditions the ripple geometry, ripple migration, suspended sand concentrations and the sand transport depend on flow and bed history as well as on the prevailing flow. This review examines previous laboratory and field studies of wave-generated ripple regime sand transport with these issues in mind.

The review is a precursor to a new programme of experiments on ripple regime sediment transport processes to be carried out in the Aberdeen Oscillatory Flow Tunnel (AOFT) as part of the SANDPIT project. The experiments will involve oscillatory flow only. For this reason the review concentrates on ripple regime transport under wave-only conditions and little reference is made to studies involving waves plus currents. The review places more emphasis on laboratory work involving field-scale flow periods and amplitudes than on laboratory studies involving short period, low amplitude flows. This is because extrapolation of results from experiments involving short period, low amplitude flows to field-scale flow conditions is very uncertain. The new experiments in the AOFT will involve field-scale flow periods and amplitudes.

The review has two main sections. The first main section is concerned with ripple geometry and the second is concerned with sand transport processes with separate consideration of suspended sediment concentrations and transport, ripple migration and net transport.

2.0 RIPPLE GEOMETRY

2.1 Introduction

Formulae and mathematical models for sediment transport in rippled-bed conditions require ripple geometry as input. Depending on the complexity of the model, ripple geometry may simply impact on an empirical calculation of bed roughness and subsequent empirical calculation of sediment transport, or it may impact on the detailed flow and sediment behaviour around individual ripples predicted by a computational fluid dynamics

simulation. In both cases the ripple geometry must be known *a priori*. Boundary roughness in unsteady oscillatory flows over movable noncohesive beds is a function of skin friction, form drag and near-bed sediment transport (Grant and Madsen, 1982). Skin friction is a function of grain size; form drag is a result of the bed morphology. Grant and Madsen (1982) found that ripples are responsible for the majority of roughness under waves when ripple steepness is greater than 0.1. Studies by Drake and Cacchione (1989), Vincent et al. (1991), Vincent and Downing (1994), Li et al. (1996) and Masselink and Pattiaratchi (2000) show that ripple geometry significantly affects the sediment resuspension coefficient which is important for estimating suspended sediment concentration profiles.

Empirical formulae based on field and laboratory observations have been developed which relate ripple height, length or steepness to the flow and sediment parameters (e.g. Inman, 1957; Dingler, 1974; Miller and Komar, 1980; Nielsen, 1981; Grant and Madsen, 1982; Vongvisessomjai, 1984; van Rijn, 1989; Wikramanayake, 1993; Wiberg and Harris, 1994; Mogridge et al., 1994). The formulae tend to perform well for the range of conditions they were developed under, but perform poorly outside that range. Many predictive formulae are heavily based on empirical data from laboratory wave flume experiments in which the flow is regular, short period and low amplitude and in which the ripples are in equilibrium with the flow. These models do not generally perform well against measured data from large-scale laboratory experiments involving regular flows with field-scale periods and orbital amplitudes (O'Donoghue and Clubb, 2001). In field conditions ripples occur under irregular flows. Also, the ripples may not be in equilibrium with the flow conditions under which they have been measured. For these reasons a number of studies have shown poor agreement between predicted and field measurements of ripple geometry (Kos'yan, 1988; Osborne and Vincent, 1993; Li et al., 1996; Doucette, 2002b).

2.2 Ripple geometry in irregular flows

Irregular flows have been used in some laboratory studies in order to better model natural environments. There are conflicting results regarding the degree of difference in ripple geometry produced under regular and irregular flow. Marsh et al. (1999) found in wave flume studies that irregular waves simulated from field measurements did not produce ripples that fit the ripple geometry prediction models they tested. The models were found to perform better under monochromatic waves. They suggest that it is rather difficult to change the wavelength of ripples once they have formed; under field conditions, with a broad wave spectrum, there may be no particular near-bed orbital diameter of sufficient dominance to force the bed to re-form. This means that the bed history is as important as the hydrodynamic conditions in determining ripple geometry. In large-scale oscillatory flow tunnel experiments, Ribberink & Al-Salem (1994) found a substantial decrease in ripple size under asymmetric and random flows compared with regular flows. In contrast, Williams et al. (2000), working with 2 sands ($D_{50}=0.33\text{mm}$ and 0.16mm) in a very large wave flume, found that ripple dimensions under regular and irregular waves were in good

agreement with those predicted by Nielsen's (1992) formula for regular flows. Vincent et al. (2001) also measured ripples under regular and irregular waves in a large wave flume. For a sand size of 0.23mm, they report ripples of similar magnitude ($\eta=5\text{-}20\text{mm}$, $\lambda=200\text{-}400\text{mm}$) under regular and irregular "groupy" waves of similar significant wave height (with $T=6.5\text{s}$, $d\approx 0.9\text{m}$) but the ripples were superimposed on much larger bedforms ($\eta=0.08\text{m}$, $\lambda=2\text{m}$) in the case of the irregular waves. In small-scale wave flume experiments, Faraci & Foti (2002) also found little difference in ripples generated by regular and irregular waves but found that the equilibrium morphology was reached through different mechanisms.

The total number and range of laboratory studies involving field-scale irregular flows is small. Further research is needed to better define the differences in ripples produced under regular and irregular flows so that the applicability of existing regular flow data and knowledge to field-type irregular flow conditions can be determined.

2.3 Ripple geometry in non-equilibrium conditions

O'Donoghue and Clubb (2001) observed in their large-scale flow tunnel experiments that, depending on the mobility, it can take many hours for equilibrium ripple geometry to be reached in a given constant flow (of the order of 20 hours for their low mobility experiments). They conclude that, because it takes time for ripples to grow towards equilibrium and for established ripples to respond to a change in the flow, ripple geometry in the field at any given instant may not be the equilibrium geometry corresponding to the flow condition at that instant. There is evidence from the field to support this view. Recent developments in remote sensing technology has allowed high frequency accurate measurements of ripple dimension and pattern in sandy shoreface and nearshore environments (e.g. Hay & Wilson, 1994; Thornton et al., 1998; Crawford and Hay, 1998; 2001; Traykovski et al., 1999; Hanes et al., 2001; Bell & Thorne, 1997; Bell et al., 1998). While these studies provide detailed measurements of ripple dimensions and associated hydrodynamic conditions, there is difficulty determining whether the bedforms are actually in equilibrium with the flow under which they have been measured. This is due to the unknown time scale for ripple adjustment to the evolving flow. For example, Osborne & Vincent (1993) found that predictive models for ripple geometry performed poorly in macrotidal environments and attributed this partially to the rapidly changing hydrodynamic conditions resulting from tidal water level fluctuations. Hanes et al. (2001) present extensive measurements of ripple geometries in the field. They found both short and long wave ripples to exist simultaneously but only the short wave ripples fit the models. This suggests that the longer wave ripples had formed under previously more energetic flows and had not adjusted to the prevailing flow conditions. They were possibly relic features because insufficient time had passed for the bed to reach an equilibrium state under the new conditions. Similar observations were made by Traykovski et al. (1999) who observed hysteresis in ripple geometry during storm growth and decay: as the storm approaches the ripples grow quickly in response to the increasing near-bed flow but the large ripples

created by the high flows maintain their size for some considerable period of time after the storm has passed and the near-bed flow has diminished.

It is clear from the foregoing that more research is needed to better understand the time scales at which ripples respond to a change in the prevailing flow conditions. Fundamental questions of the following need to be addressed: What is the time to equilibrium ripple geometry for given flow and bed conditions and how does this time depend on the initial bed geometry? Put another way: What are the time scales of change in ripple geometry for ripples generated by oscillatory flow A subject to new oscillatory flow B?

2.4 Two-dimensional and three-dimensional ripples

Geometry formulae for wave-generated sand ripples apply to two-dimensional (2-d) ripples, i.e. long-crested, parallel ripples with height and length constant over a large bed area. However, three-dimensional (3-d) ripples have been observed on numerous occasions in laboratory and field settings (e.g. Boyd et al., 1988; Osborne & Vincent, 1993; Ribberink and Al-Salem, 1994) and temporal and spatial sequences of alternating 2-d and 3-d patterns have been observed in a number of studies in the field and in the laboratory (Boyd et al., 1988; Osborne and Vincent, 1993; Doucette, 2000; Crawford and Hay, 2001; O'Donoghue and Clubb, 2001; Traykovski et al., 1999).

3-d ripples are often attributed to the presence of mean currents oblique to the oscillatory motion but these patterns have been observed under regular flows in laboratory settings where mean currents were not present (Lofquist, 1978; Sato and Horikawa, 1986; O'Donoghue & Clubb, 2001) and in field settings where mean currents were negligible (Doucette, 2000). O'Donoghue & Clubb (2001) observed, under large-scale oscillatory flows, that as ripples develop from a plane bed they first form small 2-d ripples and then proceed to a 3-d transitory stage before the formation of the final larger 2-d equilibrium ripples. The observed 3-d transitional stage can persist for many hours and suggests that 3-d ripples observed in field studies may not, in some cases, be in equilibrium with the flow.

Because the ripple geometry predictive formulae do not apply to 3-d ripples and because suspension mechanisms and net transport may be very different for 2-d and 3-d ripples, it is important to be able to predict the occurrence of 2-d/3-d ripples. Doucette (2000) observed from measurements of ripples at a number of nearshore field sites that 2-d ripples occurred only in cases of relatively coarse sand, with D_{50} greater than approximately 0.3mm. Sato and Horikawa (1986) recorded both 2-d and 3-d ripples in their tunnel experiments with 0.18mm sand and flow periods between 3 and 7 seconds. They noted a "drastic" difference in sand transport mechanics between the two bed types with much less net transport in the case of 3-d ripples. They suggest that the occurrence of 2-d or 3-d ripples depends on the relative orbital diameter (d/D_{50}) and the Shields parameter. O'Donoghue and Clubb (2001) and Loftquist (1978) both found that 2-d ripples eventually occurred in their laboratory experiments with larger sands but that 3-d ripples occurred in

conditions of relatively fine sand and field-scale flow orbital diameters. O'Donoghue & Clubb (2001) found that previously-suggested simple criteria for the occurrence of 2-d/3-d ripples (e.g. Sato and Horikawa, 1986) fail when applied to their results covering a wide range of sand sizes and flow conditions.

Present understanding of the occurrence of 2-d/3-d ripples is poor. The problem is complicated by the fact that it depends not only on flow and sand properties (possibly including the sediment sorting) but also on flow duration. Given that ripple dimensions and transport processes may be very different for 2-d and 3-d ripples, research is needed to better establish criteria for the occurrence of 2-d and 3-d ripples and to examine how well formulae for 2-d ripple geometry predict the major dimensions of 3-d ripples.

3.0 RIPPLE REGIME SEDIMENT TRANSPORT

3.1 Introduction

Wave-generated sediment transport over rippled beds is considered to have two main components – transport due to suspended sediments and transport due to ripple migration. These are best described by considering the case of ripples in regular asymmetric flow in which the onshore velocity maximum is substantially greater than the offshore velocity maximum (velocity time-history corresponding to Stokes 2nd order wave). For this case the ripples are asymmetric with steeper onshore sides than offshore sides and there is asymmetry in the transport mechanisms between the onshore and offshore parts of the flow cycle. During the onshore flow, the high onshore velocities transport a large volume of sand up the offshore side of the ripple and over the ripple crest. Some of this sand is entrained in the developing lee vortex, which also entrains sand from the ripple's onshore flank. The vortex becomes very large as the flow slows, entraining more sand as it does so. It is ejected into the main flow above the ripple at about the time of flow reversal, making a relatively large contribution to the *offshore* directed suspended sediment transport. Much of the sand that has been carried up the offshore side and over the ripple crest during the onshore flow does not get carried into suspension by the lee side vortex. Instead it slumps down the onshore side contributing to onshore shift of the ripple position, i.e. it contributes to *onshore* ripple migration. The same processes occur during the offshore half cycle but because of the lower offshore velocities and the less steep offshore ripple flank, (1) a much weaker vortex is produced resulting in much less onshore directed suspended sediment transport and (2) much less sediment is carried up the steep onshore side and over the ripple crest resulting in less, if any, offshore ripple migration compared to onshore migration. For this case of regular asymmetric flow therefore, the net suspended transport is offshore while the ripple migration is onshore; the total net transport depends on the relative magnitudes of the suspended and ripple migration transports. Which of the two transport mechanisms dominates depends on the ripple geometry, the flow and the

sediment characteristics. For conditions involving relatively large magnitudes of suspended sediment, net transport is offshore and is opposite to the direction of ripple migration.

While these processes are understood qualitatively, a lack of measurements in well-controlled conditions means that quantitative understanding is poor. Here we look at previous laboratory and field studies of (1) sediment suspension and suspended sediment transport over ripples, (2) ripple migration and (3) net transport. Our particular interest remains on irregular flows and non-equilibrium conditions.

3.2 Suspended sediment

Suspended sand concentration above a rippled bed depends on time (wave phase), height above the bed and horizontal location relative to the ripple crest. The suspended sediment concentration profile (concentration c as function of height z above the bed) is therefore both time- and horizontally-varying. Laboratory-based research on suspended sediment above rippled beds has largely been concerned with establishing the time- and horizontally-*averaged* concentration profile for given flow (wave) and bed conditions. Much of this research has been based in small wave flumes or small flow tunnels (e.g. Nakato et al., 1977; McFetridge and Nielsen, 1985; Bosman and Steetzel, 1986; Ono et al., 1994). Laboratory studies involving the longer period, larger amplitude flows typical of field-scale conditions have been carried out in large oscillatory flow tunnels (Hayakawa et al., 1983; Ribberink and Al-Salem, 1994; Clubb, 2001) and in large wave flumes and basins (Williams et al., 2000; Vincent et al., 2001; Villard et al., 2000; Villard and Osborne, 2002). Ribberink and Al-Salem (1994) measured time- and horizontally-*averaged* concentration profiles for a relatively large number of sinusoidal flows and a few irregular flows over a sand bed with $D_{50}=0.21\text{mm}$. Clubb (2001) used a carousel-based suction sampling system to obtain time- and horizontally-*varying* concentration measurements at many locations above large 2-d ripples in regular sinusoidal and asymmetric flows over a 0.34mm sand bed. He found that sinusoidal and asymmetric flows with the same rms velocity and period resulted in very similar time- and horizontally-*averaged* concentration profiles despite very large differences in the time- and horizontally-*varying* concentrations in the two flow types. Williams et al. (2000) also used suction sampling to measure time- and horizontally-*averaged* concentration profiles for two different sand beds ($D_{50}=0.33\text{mm}$ and 0.16mm) under regular and irregular waves in a large wave flume. They show that a diffusion-based formula for concentration profile describes the measured concentration profiles very well, for both regular and irregular wave conditions. The measured profiles were in relatively poor agreement with the convection-based formula of Nielsen (1992).

Acoustic backscatter systems (ABS) enable easier measurement of time-varying concentration profiles compared to suction sampling. ABS has been used in recent years in a number of laboratory studies conducted in large wave flumes and wave basins involving regular and irregular waves. Measurements show that suspension processes in irregular

flows are more complicated than in regular flows. For example, Villard & Osborne (2002) found that the suspended sediment concentrations in irregular flows are influenced by the recent history of the flow, with large suspension events associated with the pairing of antecedent and developing vortices due to the passage of wave groups. Vincent et al. (2001) compared suspended sediment concentrations measured in regular and irregular waves and found that regular waves suspend an order of magnitude more sediment than “groupy” irregular waves with similar significant wave height.

ABS has also been used to measure suspended sand concentrations over ripples in the field (e.g. Vincent and Green, 1991; Vincent and Downing, 1994; Osborne and Vincent, 1996; Webb and Vincent, 1999; Green and Black, 1999). Field studies are complicated by the lack of control over the many variables involved in determining the sand suspensions. For example, Vincent and Green (1991) measured very different suspended sediment patterns at two different times at the same location under very similar wave conditions. The difference is assumed to be due to different ripples being present at the two times. Vincent and Green conclude that sand size and near-bed flow are not sufficient to determine ripple dimensions and, consequently, are insufficient to determine the sand suspension. As discussed in Section 2.3, the duration of the flow and the bed history are also important in determining the ripple geometry and related sediment suspension.

The complexities of suspended sediment transport under field conditions in which the waves are irregular and sometimes bimodal and the ripples are changing with time are illustrated in the field measurements of Brander and Greenwood (1993) and Doucette (2000). Brander and Greenwood (1993) found that the wave component of suspended sediment transport over steep ripples was directed onshore, but as ripple steepness declined the direction of transport at higher elevations reversed. Doucette (2000) found mainly onshore directed suspended sediment transport measured at 0.05m above the bed for steeper 2-d ripples and onshore and offshore transport at different frequencies over flatter 2-d and 3-d ripples.

It is clear that the number of controlled, large-scale experiments for which suspended sediment concentration data have been obtained is relatively few and the range of conditions covered by the experiments is small. More data is available from small-scale experiments but scale effects make application of results from these experiments to field-scale conditions uncertain. There remains a lack of data from controlled, large-scale experiments to address questions like: (1) How do suspended sediment concentrations and transport in irregular flows compare with suspended sediment concentrations and transport in “equivalent” regular flows? Can results from regular flow experiments be applied to irregular flow conditions? (2) What are the suspended sediment concentrations and suspended sediment transport rates in non-equilibrium conditions? Or: What are the suspended sediment concentrations and suspended sediment transport rates for flow A over

ripples generated by oscillatory flow B? Of course these questions cannot be addressed independently of the corresponding ripple geometry questions.

3.2 Ripple Migration

Migration of ripples under oscillatory conditions is poorly understood because of the lack of controlled, systematic studies of the migration process. Faraci & Foti (2002) observed ripple migration in the laboratory for irregular waves but the wave periods were relatively short ($<5s$). Only Ribberink and Al-Salem (1994) and Clubb (2001) present measures of ripple migration from field-scale laboratory experiments. Ribberink and Al-Salem measured ripple migration for test conditions involving a 0.21mm sand and irregular flows. They reported 2-d and 3-d small ripples ($\eta < 15mm$, $\lambda < 100mm$) with high onshore migration rates (6-30mm/min). Net transport in the Ribberink and Al-Salem experiments was onshore, which means that the onshore transport due to ripple migration was greater than the offshore transport due to suspended sediment. This behaviour is different to that described by Clubb (2001) for large 2-d ripples ($\eta = 70-140mm$, $\lambda = 510-770mm$) comprising 0.34mm sand in regular asymmetric flows. In Clubb's case the large ripples migrated onshore with speeds in the range 2.5-8.5mm/min but high sand suspensions occurred over the large ripples so that the total net transport was offshore. Clubb showed that the onshore transport was determined by ripple migration and could be reasonably well estimated from the product of ripple height and migration speed. He also showed that the transport processes lead to sediment sorting with coarser sand moving onshore with the ripple migration and finer sand moving offshore in the sand suspensions.

Field measurements of ripple migration under waves have been in rips (Sherman et al., 1993), under strong tidal currents (Sternberg, 1967; Kachel and Sternberg, 1971; Langhorne, 1981; 1982; Yang, 1986) on the deeper shoreface (Li et al., 1997; Boyd et al., 1988; Amos et al., 1999, Traykovski et al., 1999) and under wave-only conditions in the nearshore (Dingler and Inman, 1976; Osborne and Vincent, 1993; Vincent and Osborne, 1993; Crawford & Hay, 2001; Doucette, 2002a).

Boyd *et al.* (1988) measured ripple migration in a field study where the prevailing conditions are summarised as $T=4-11s$, orbital diameter $d=0.2-1.9m$, and sand size $D=0.11mm$. Ripple migration rates in the range $0 \leq v_r < 0.8mm/min$ were generally observed but migration rates of $v_r=1.6mm/min$ were observed under one storm event (with $T \approx 11s$ and $d \approx 1.9m$ and ripples with $\lambda \approx 0.1m$). Migration was predominantly onshore but offshore migration was observed under the highest waves during two storms. Boyd et al. (1988) found no consistent relationship between ripple migration and flow velocity mean and skewness, whereas Vincent and Osborne (1993) found a positive relationship between the migration rate of small ripples and shear stress but found no relationship between the migration rate of larger ripples and shear stress. These different observations are possibly due to the fact that they were made in different environments, over different sized ripples, but they may also be a result of changing relationships around a break-off point. For

example, under combined waves and currents on the shoreface, Amos *et al.* (1999) found ripple migration rate increased up to a break-off point with increasing steady flow and then decreased above the break-off point. An additional explanation is required for ripple migration rate under purely oscillatory flows.

Traykovski *et al.* (1999) measured ripple migration in the field for wave conditions with $T=7-10s$, $d=0.2-1.0m$ and sand with $D\approx 0.4mm$. The study included one event with $T=16-18s$ and $d\approx 2m$ for which the largest ripples with length $\lambda\approx 1m$ were measured. The migration rate of the largest ripples was $\approx 0.5mm/min$ and the average migration rate reported over the study period was $0.17mm/min$. For the majority of the study, ripple migration was directed onshore (opposite to the direction of the suspended sand transport) although under transient conditions the ripple crests appeared to move offshore, especially when ripples were adjusting to a change in angle of wave incidence. Traykovski *et al.* (1999) concluded that ripple migration is related to bed load transport and their description of the transport processes follows that outlined earlier (Section 3.1): the larger onshore velocities generate asymmetry in the bed load and near-bed transport with the net effect being coarse sand moving onshore near the bed feeding ripple migration, whilst the asymmetry between vortices either side of the ripple crest cause a net offshore transport of the finer sediment as suspended load.

Crawford & Hay (2001) measured the migration of small, long-crested, anorbital ripples in the nearshore (3.2m mean water depth) in conditions of relatively high wave energy using a high-resolution laser-video bed profiling system over the course of a storm event. They observed small, low steepness ripples with $\lambda\approx 85mm$ and $\eta\approx 3mm$ that migrated offshore during storm growth and onshore during storm decay. Migration speeds up to $v_r=7mm/min$ were measured. Ripple migration velocities were highly correlated to near-bed wave orbital velocity skewness. Doucette (2002) made similar observations of ripple migration: large 2-d ripples were observed to migrate onshore during a narrow-banded swell period between two sea breeze events; during the sea breeze events where swell and sea were present, the ripples were observed to migrate offshore. These studies suggest that the wave spectral distribution is an important factor in determining ripple migration direction.

The conclusion here is similar to that for suspended sediments, i.e. the number of controlled, large-scale experiments for which ripple migration has been studied is very limited so that quantitative understanding of ripple migration under waves is poor. Further controlled, large-scale experimental research is needed to study ripple migration under regular and irregular oscillatory flows and for non-equilibrium conditions. Because of the inter-dependence of the processes, ripple migration should not be studied independently of ripple geometry, suspended sediments and sediment transport.

3.4 Sediment transport

Net transport over rippled beds has been measured in early laboratory experiments using oscillating trays in still water (Manohar, 1955; Kalkanis, 1964; Abou-Seida, 1965) and more recently in wave flumes with short period ($< 3s$), low orbital amplitude flows (Ishida et al., 1983; Vongvisessomjai et al., 1986; Sistermans, 2001). Laboratory experiments with flow periods and amplitudes closer to those of typical field conditions have been carried out in oscillatory flow tunnels by Sato and Horikawa (1986: 3-5s regular and irregular asymmetric flows and 0.18mm sand), Ribberink and Al-Salem (1994: Series B, 5-9.1s irregular asymmetric flows and 0.21mm sand) and Clubb (2001: 5s and 10s regular asymmetric flows with 0.34mm sand).

Clubb (2001) and Sato and Horikawa (1986) measured transport for cases of equilibrium ripples and found the net transport to be *offshore* directed in all cases. Sato and Horikawa also measured transport as the ripples developed from an initially flat bed and showed that net transport was initially *onshore* before becoming increasingly offshore as the equilibrium ripples developed. Vongvisessomjai (1986) also measured maximum onshore transport when ripples were beginning to form, before decreasing as the equilibrium ripple was reached. These results point again to the importance of flow duration, bed history and time-scales of bed evolution in determining the sediment transport. In contrast to Clubb (2001) and Sato and Horikawa (1986), Ribberink and Al-Salem (1994) measured net *onshore* transport in each of their irregular asymmetric flow ripple regime experiments. The Ribberink and Al-Salem ripples are reported as being small ($\eta < 15mm$, $\lambda < 100mm$) with definite onshore migration. The net onshore transport may have been a result of low sand suspensions at flow reversals caused by the ripples being small, resulting in low offshore suspended transport compared with the onshore ripple migration.

Sato and Horikawa (1986) do not present transport results for their irregular flows (other than to say that the transport is much less than for their regular flows). This means that to the authors' knowledge the Ribberink and Al-Salem's results covering 6 irregular flows and 1 sand size are the only laboratory (controlled) results available for transport over wave-generated ripples in field-scale *irregular* flows.

Measurements of total transport in the field are very problematic. They require measurements of ripple migration and measurements of the vertical velocity and concentration profiles above the rippled bed in order to obtain the suspended sediment flux. Because of the strong horizontal variation in velocity and concentration, the velocity and concentration profiles must be measured at the same horizontal position relative to the ripple crest, something that is very difficult to achieve in field conditions. Field measurements of transport have been reported by Vincent & Green (1990), Li *et al.* (1997) and Traykovski *et al.* (1999). Traykovski *et al.* measured ripple migration and time-varying velocity and suspended sediment profiles at a site where the sand size is $D \approx 0.4mm$. The net suspended sediment transport was wave-dominated and was offshore

directed while the ripple migration was onshore. They also found that bedload model calculations forced with measured wave velocities predict bedload sediment transport magnitude and direction consistent with observed ripple migration rates.

4.0 CONCLUSION

Despite the large number of laboratory studies, data from controlled, systematic, large-scale experiments are very limited. At the same time the lack of control over the many variables involved, including the possibility of non-equilibrium conditions, means field data are complex and interpretation is often problematic. For these reasons quantitative understanding of important ripple regime transport processes is currently poor and much more research is needed in order to establish good predictive models. This review has been conducted as a precursor to a new programme of field-scale, oscillatory flow, ripple regime experiments to be carried out in the Aberdeen Oscillatory Flow Tunnel. For this reason our recommendations for further research, based on the review, are focussed on what the new experimental programme should address. There are two main areas:

Irregular flow Data from regular flow experiments are useful, especially in terms of isolating particular processes and informing the development of process-based numerical models, but their applicability to real, irregular flow conditions needs to be determined. New field-scale experiments are needed to compare ripple geometry and sand transport processes – suspension, migration and transport - for irregular and “equivalent” regular flows.

Ripple evolution and non-equilibrium transport Previous laboratory studies have tended to concentrate on “equilibrium” ripples but non-equilibrium ripples are common in field conditions. Knowledge of the time scales at which ripples adjust to changing flow conditions is important because of the effect of different bed morphologies on suspended sediment concentrations and sediment transport. The impact of the lag in ripple response to changing hydrodynamic conditions on the resulting net sediment transport is not known. The presence of ripples that are not in equilibrium with the flow may produce significantly different net sediment transport than when equilibrium ripples are present. New experiments are needed to establish time scales of ripple development in response to a change in flow conditions. A number of different scenarios need to be studied: (a) initial bed is flat, (b) initial bed comprises ripples that are substantially *larger* than the ripples associated with the new flow and (c) initial bed comprises ripples that are substantially *smaller* than the ripples associated with the new flow. Measurements of the (time-dependent) ripple geometry and sand transport processes need to be made in cases where the ripples are slow to develop in the new flow, i.e. in cases where the non-equilibrium conditions persist for long durations.

APPENDIX

Laboratory studies of ripples in IRREGULAR flow

Authors	Year	Facility	Flow Conditions	Sand Size (mm)	Comments
Sato & Horikawa	1986	Oscillatory Flow Tunnel (Tokyo)	T=3.9s, 3.68s do=16-51cm	0.18	Regular and irregular asymmetric flows. Net sand transport rate measured.
Osborne & Vincent	1996	Wave basin (NRC, Ottawa)	T=3.9s H=0.2-0.4m depth=1.6m	0.15,0.25 0.45,0.485	Irregular waves synthesized from field measurements. Mainly suspended sand measurements.
Ribberink & Al-Salem	1994	Oscillatory Flow Tunnel (LOWT, Delft)	T=6.5s, 12s urms=0.2-0.92m/s	0.21	Regular and irregular, ripple and sheet-flow regime Flows based on JONSWAP and 2 nd order Stokes Geometry, migration, c-profiles, net sediment transport rate measured. 6 irregular ripple regime experiments.
Marsh et al.	1999	Wave basin (NRC, Ottawa)	T=3-4s do=0.2-1.06m	0.315	Waves from field site and monochromatic waves. Ripple geometry mainly.
Villard et al.	2000	Wave flume (NHL, Ottawa)	8 wave groups U up to 0.7m/s T=4-5s	0.25	Monochromatic, bichromatic and waves from field site. Influence of wave groups on ssc over vortex ripples. ABS measures of temporal and spatial variations in ssc.
Williams et al.	2000	Large wave flume (Delta flume)	T=5s H=0.5,0.75,1,1.25m	0.162 and 0.329	Reg and irreg Jonswap waves Irregular waves conformed to JONSWAP spectrum. Equilibrium conditions in ~60min; emphasis on averaged c-profiles
Vincent et al.	2001	Large wave Flume (Hannover)	Hs=0.6m T=6.5s depth=3.75m	0.23	3 wave conditions: 2 regular and 1 "repeating wave groups" Used multiple transducer array. Comparison of ssc for regular and irreg wave with similar Hs
Doering & Baryla	2002	Wave flume (Manitoba Univ.)	T=1.75s H=1.88,0.249,0.152m Depth=1m	0.09	Vertical velocities over ripple crests and troughs. Stokes waves, Stokes groups, & irregular waves Not investigating sediment behaviour
Villard & Osborne	2002	Wave basin (NRC, Ottawa)	T=2.7s Depth=1.6m Bed slope 1:25	0.25	Irregular waves synthesized from field measurements. Visualization of sediment suspension.
Faraci & Foti	2002	Wave flume (catania Univ.)	H=8-13cm T=1.25-4.18s Depth=28cm	0.25	Regular and irregular waves. Irregular waves conformed to JONSWAP spectrum. Used video to get ripple profiles. Measurements of ripple evolution and migration

References

- Abou-Seida, M.M., 1965. Bed load function due to wave action. Report HEL-2-11, Hydraulic Engineering Laboratory, University of California, Berkeley.
- Amos, C.L., Bowen, A.J., Huntley, D.A., Judge, J.T., and Li, M.Z., 1999. Ripple migration and sand transport under quasi-orthogonal combined flows on the Scotian Shelf. *Journal of Coastal Research*, 15, 1-14.
- Bagnold, R.A., 1946. Motion of waves in shallow water – interaction between waves and sand bottoms. *Proc. Royal Soc. of London, Series A* (187): 1-15.
- Bell, P.S. and Thorne, P.D., 1997. Application of a high resolution acoustic scanning system for imaging sea bed microtopography. 7th Int. Conf. on Electronic Engineering in Oceanography, Southampton Oceanography Centre, 23-25 June 1997.
- Bell, P.S., Thorne, P.D. and Williams, J.J., 1998. Acoustic measurements of sand ripple profile evolution under controlled wave conditions. 353-358. *Proceedings of the 4th European Conference on Underwater Acoustics*, 21-25 September 1998, Rome, Italy. Volume 1. Istituto di Acustico "O.M.Corbino", Rome, Italy.
- Bosman, J.J. and Steetzel, H.J., 1986. Time and bed averaged concentrations under waves. *Proc. 20th Int. Coastal Engng. Conf.*, 986-1000.
- Boyd, R., Forbes, D.L. and Heffler, D.E., 1988. Time-sequence observations of wave-formed sand ripples on an ocean shoreface. *Sedimentology* 35, 449-464.
- Brander, R.W. and Greenwood, B., 1993. Bedform roughness and the re-suspension and transport of sand under shoaling and breaking waves: a field study. *Proceedings of the 1993 Canadian Coastal Conference*, Vancouver, B.C., 587-599.
- Crawford, A.M. and Hay, A.E., 1998. A simple system for laser-illuminated video imaging of sediment suspension and bed topography. *IEEE J. Oceanic Eng.*, 23 (1), 12-19.
- Crawford, A.M. and Hay, A.E., 2001. Linear transition ripple migration and wave orbital velocity skewness: Observations. *J. of Geophys. Res.* 106(C7), 14,113-14,128.
- Clubb, G.S., 2001. Experimental Study of Vortex Ripples in Full Scale Sinusoidal and Asymmetric Flows. Ph.D. Thesis, University of Aberdeen
- Dingler, J.R., 1974. Wave formed ripple in nearshore sands. Ph.D. thesis, Univ. of Calif. San Diego.
- Dingler, J.R. and Inman, D.L., 1976. Wave-formed ripples in nearshore sands. *Coastal Eng.* 2109-2126.
- Doering, J.C. and Baryla, A.J., 2002. An investigation of the velocity field under regular and irregular waves over a sand beach. *Coastal Engineering*, 44, 275-300.
- Doucette, J.S., 2000. The distribution of nearshore bedforms and effects on sand suspension on low-energy, microtidal beaches in southwestern Australia. *Marine Geology*, 165, 41-61.

- Doucette, J.S., 2002a. Bedform migration and sediment dynamics in the nearshore of a low-energy sand beach in southwestern Australia. *J. Coastal Research*, 18(3), 576-591.
- Doucette, J.S., 2002b. Ripple grain size sorting and geometry prediction on low-energy sandy beaches. *Sedimentology*, 49, 483-503.
- Drake, D.E. and Cacchione, D.A., 1989. Estimates of the suspended sediment reference concentration (C_a) and resuspension coefficient (γ_o) from near-bed observations on the California shelf. *Continental Shelf Research*, 9, 51-64.
- Faraci, C. and Foti, E., 2002. Geometry, migration and evolution of small-scale bedforms generated by regular and irregular waves. *Coastal Engineering*, 47, 35-52.
- Grant, W.D. and Madsen, O.S., 1982. Movable bed roughness in unsteady oscillatory flow. *Journal of Geophysical Research*, 87(C1), 469-481.
- Green, M.O. & Black, K.P. 1999. Suspended-sediment reference concentration under waves: field observations and critical analysis of two predictive models. *Coastal Engineering*, 38, 115-141
- Hanes, D.M., Alymov, V., Chang, Y.S. and Jette, C., 2001. Wave-formed sand ripples at Duck, North Carolina. *J. Geophys. Res.*, 106 (C10), 22,575-22,592.
- Hay, A.E. and Wilson, D.J., 1994. Rotary sidescan images of nearshore bedform evolution during a storm. *Mar. Geol.* 119, 57-65.
- Hayakawa, N., Tsujimoto, G., Hashimoto, H., 1983, Velocity distribution and suspended sediment concentration over large scale ripples. *Coastal Engng. in Japan*, 26, 91-100.
- Inman, D.L., 1957. Wave-generated ripples in nearshore sands. Tech. Memo 100, Beach Erosion Board.
- Ishida, A., Hayashi, I., Takahashi, H. and Kioka, W., 1983. Modelling of onshore-offshore sediment transport over a rippled bed. *Coastal Engineering in Japan*, 26, 77-89.
- Kachel, N.B. and Sternberg, R.W., 1971. Transport of bedload as ripples during an ebb current. *Marine Geology*, 10, 229-244.
- Kalkanis, G., 1964. Transport of bed material due to wave action. US Army Coastal Engineering Research Centre. Tech. Memo no. 2.
- Khelifa, A. and Ouellet, Y., 2000. Prediction of sand ripple geometry under waves and currents. *ASCE, J. of Waterway, Port, Coastal and Ocean Engineering*, 126(1), 14-22.
- Kos'yan, R.D., 1988. Study of sand microforms in the nearshore zone. *Marine Geology*, 83, 63-78.

- Langhorne, D.N., 1981. An evaluation of Bagnold's dimensionless coefficient of proportionality using measurements of sand wave movement. *Marine Geology*, 43, 49-64.
- Langhorne, D.N., 1982. A study of the dynamics of a marine sandwave. *Sedimentology*, 29(4), 571-594.
- Li, M.Z., Amos, C.L. and Heffler, D.E., 1997. Boundary layer dynamics and sediment transport under storm and non-storm conditions on the Scotian Shelf. *Marine Geology*, 141, 157-181.
- Li, M.Z., Wright, L.D. and Amos, C.L., 1996. Predicting ripple roughness and sand resuspension under combined flows in a shoreface environment. *Marine Geology*, 130, 139 -161.
- Lofquist, K.E.B., 1978. Sand ripple growth in an oscillatory-flow water tunnel. U.S. Army Coastal Engineering Research Centre, Tech. Paper no. 78-5.
- Manohar, M., 1955. Mechanics of bottom sediment movement due to wave action. US Army Corps of Engineers, Beach Erosion Board, Tech. Memo no. 75.
- Marsh, S.W., Vincent, C.E. and Osborne, P.D., 1999. Bedforms in a laboratory wave flume: an evaluation of predictive models for bedform wavelengths. *Journal of Coastal Research*, 15(3), 624-634.
- Masselink, G. and Pattiaratchi, C., 2000. Tidal asymmetry in sediment resuspension on a macrotidal beach in northwestern Australia. *Marine Geology*, 163, 257-274.
- McFetridge, W.F. and Nielsen, P., 1985. Sediment suspension by non-breaking waves over rippled beds. Coastal and Oceanographical Engineering Department, University of Florida, Gainesville, Tech. Rep. UFL/COEL-85/005.
- Miller, M.C. and Komar, P.D., 1980. A field investigation of the relationship between oscillation ripple spacing and the near-bottom water orbital motions. *J Sed. Petrol.*, 50(1), 0183-0191.
- Mogridge, G.R., Davies, M.H. and Willis, D.H., 1994. Geometry prediction for wave-generated bedforms. *Coastal Engineering*, 22, 255-286.
- Nakato, Y., Locher, F.A., Glover, J.R. and Kennedy, J.F., 1977. Wave entrainment of sediment from rippled beds. *ASCE, J. of the Waterway, Port, Coastal and Ocean Division*, 103, 83-99.
- Nielsen, P., 1981. Dynamics and geometry of wave-generated ripples. *J. Geophys. Res.*, 86(c7), 6467-6472.
- Nielsen, P., 1992. Coastal bottom boundary layers and sediment transport. World Scientific.
- O'Donoghue, T. and Clubb, G.S., 2001. Sand ripples generated by regular oscillatory flow. *Coastal Engineering*, 44, 101-115.

- Ono, M., Kim, K.H., Sawaragi, T., Deguchi, I., 1994. Suspended sediment caused by waves and currents. Proc. 24th Int. Coastal Engng. Conf., 2476-2487.
- Osborne, P.D. and Vincent, C.E., 1993. Dynamics of large and small scale bedforms on a macrotidal shoreface under shoaling and breaking waves. *Marine Geology*, 115, 207-226.
- Osborne, P.D. and Vincent, C.E., 1996. Vertical and horizontal structure in suspended sand concentrations and wave-induced fluxes over bedforms. *Marine Geology* 131, 195-208.
- Ribberink, J.S. & Al-Salem, A., 1990. Bedforms, sediment concentrations and sediment transport in simulated wave conditions. Proceedings 22nd Int. Coastal Engng. Conf., 2318-2331.
- Ribberink, J.S. & Al-Salem, A.A., 1994. Sediment transport in oscillatory boundary layers in cases of rippled beds and sheet flow. *Journal of Geophysical Research*, 99, 12707-12727.
- Sato, S. and Horikawa, K., 1986. Laboratory study on sand transport over ripples due to asymmetric oscillatory flows. Proc. 20th Int. Coastal Engng. Conf., 1481-1495.
- Sherman, D.J., Short, A.D., and Takeda, I., 1993. Sediment mixing-depth and bedform migration in rip channels. *Journal of Coastal Research*, 15, 39-48.
- Sisttermans, P.G.J., 2001. Multi-fraction net sediment transports by irregular waves and a current. ASCE, Proc. Coastal Dynamics '01, 588-597.
- Sternberg, R.W., 1967. Measurements of sediment movement and ripple migration in a shallow marine environment. *Marine Geology*, 5, 195-205.
- Thornton, E.B., Swayne, J.L. and Dingler, J.R., 1998. Small-scale morphology across the surf zone. *Marine Geology*, 145, 173-196.
- Traykovski, P., Hay, A.E., Irish, J.D. and Lynch, J.F., 1999. Geometry, migration, and evolution of wave orbital ripples at LEO-15. *J. Geophys. Res.*, 104(C1), 1505-1524.
- van Rijn, L.C., 1989. *Handbook of Sediment Transport by Currents and Waves*. Delft Hydraulics, Delft, 450p.
- Villard, P.V. and Osborne, P.D., 2002. Visualization of wave-induced suspension patterns over two-dimensional bedforms. *Sedimentology*, 49, 363-378.
- Villard, P.V., Osborne, P.D. and Vincent, C.E., 2000. Influence of wave groups on SSC patterns over vortex ripples. *Cont. Shelf Res.*, 20 (17), 2391-2410.

- Vincent, C.E. and Downing, A., 1994. Variability of suspended sand concentrations, transport and eddy diffusivity under non-breaking waves on the shoreface. *Cont. Shelf Res.*, 14(2/3), 223-250.
- Vincent, C.E. and Green, M.O., 1990. Field measurements of the suspended sand concentration profiles and fluxes and of the resuspension coefficient over a rippled bed. *J. Geophys. Res.*, 95, 11591-11601.
- Vincent, C.E. and Green, M.O., 1991. Patterns of suspended sand. In: Soulsby, R. and Bettress, R. (Editors), *Sand Transport in Rivers, Estuaries and the Sea*. Balkema, Rotterdam. p.117-124.
- Vincent, C.E., Hanes, D.M. and Bowen, A.J., 1991. Acoustic measurements of suspended sand on the shoreface and the control of concentration by bed roughness. *Marine Geology*, 96, 1-18.
- Vincent, C.E., Hanes, D.M., Dohmen-Janssen, C.M., Klopman, G., McLean, M., Obhrai, C., and Ribberink, J.S., 2001. Suspension by regular and groupy waves over bedforms in a large wave flume (SISTEX99). *Coastal Dynamics'01*, 303-312.
- Vincent, C.E. and Osborne, P.D., 1993. Bedform dimensions and migration rates under shoaling and breaking waves. *Continental Shelf Research*, 13(11), 1267-1280.
- Vongvisessomjai, S., 1984. Oscillatory ripple geometry. *J. Hydraulic Eng.*, 110 (3), 247-266.
- Webb, M.P. & Vincent, C.E. 1999. Comparison of time-averaged acoustic backscatter concentration profile measurements with existing predictive models. *Marine Geology*, 162, 71-90.
- Wiberg, P.L. and Harris, C.K., 1994. Ripple geometry in wave-dominated environments. *J. Geophys. Res.*, 99(C1), 775-789.
- Wikramanayake, P.N., 1993. Velocity profiles and suspended sediment transport in wave-curent flows. PhD Thesis, Massachusetts Institute of Technology 285 pp.
- Williams, J.J., Bell, P.S., Thorne, P.D., Trouw, K., Hardcastle, P.J., and Humphery, J.D. 2000. Observed and predicted vertical suspended sediment concentration profiles and bedforms in oscillatory-only flow. *J. of Coastal Research*, 16(3), 698-708.
- Yang, C.S., 1986. On Bagnold's sediment transport equation in tidal marine environments and the practical definition of bedload. *Sedimentology*, 33(4), 465-486.