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A Laboratory Study of Sand Bar Evolution

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ABSTRACT

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A series of experiments was carried out in the central test section of a 10 m long wave flume, to study the development and stability of sand bars. Bar formation was initiated by (monochromatic) waves which were generated by a wave-maker at one end of the flume, and partially reflected by a beach at the other end. Sediment grains accumulated into bars with spacings equal to half the local surface wavelength. The positions of the bars relative to the nodes and antinodes of the wave envelope depended upon the type of sediment used. As the bars grew in size the reflection coefficient measured on their up-wave side increased significantly, suggesting a coupling between bar growth and the resonant (Bragg) reflection of the incident waves. In some experiments, stable equilibrium bar profiles were obtained. However, in others, the wave field became unstable, with wave breaking over the bar crests causing a flattening of the bed. Two modes of sediment transport were identified: movement of fine grains in suspension by the residual mass transport circulation associated with a partially standing wave field, and movement of both coarse and fine grains by vortex formation and shedding above small-scale ripples on the bed. When the net transport was such that coarser grains accumulated at the bar crests, this had a stabilising effect on the bars.

ADDITIONAL INDEX WORDS: *Wave flume, Bragg reflection, sediment transport, vortex, ripples, wave envelope.*

INTRODUCTION

Longshore sand bars have been observed outside the breaker zone on many natural beaches. Bar patches may consist of up to about 20 ridges with crest to trough heights of the order of a metre, and with spacings from tens of metres to several hundred metres. There have been many field studies of such systems, for example by SAYLOR and HANDS (1970) in Lake Michigan, by SHORT (1975a) in the Alaskan Arctic and by DETTE (1980) in the Baltic Sea. In general, the bar spacing has been found to increase offshore with increasing depth.

There have been many attempts to explain the formation of nearshore bars. These include the convergence of sediment beneath partially-standing waves resulting from reflection of the incident waves (*e.g.* CARTER *et al.*, 1973; SHORT, 1975b; and BOWEN, 1980); the presence of leaky long-wave modes caused by time-variation of the breakpoint (SYMONDS *et al.*, 1982; and SYMONDS and BOWEN, 1984) or by large progressive edge waves with 'infragravity' periods (HUNTLEY, 1976); and the harmonic decomposition of incident waves leading to non-permanent waves moving in and out of phase (BOCZAR-KARAKIEWICZ and DAVIDSON-ARNOTT, 1987). There are also a number of suggested formative mechanisms in which surf-zone processes dominate. For example, EVANS (1940) attributes bar formation to vortex action at the breakpoint of plunging breakers (forming a 'breakpoint' bar). DYHR-NIELSON and SØRENSEN (1970) describe shoreward transport outside the breakpoint, along with seaward transport (the 'undertow') inside the breakpoint, leading to convergence in the breaker zone.

Once bars are formed it is believed that they may cause enhanced reflection of the incoming waves (*e.g.* DAVIES, 1982; and MEI, 1985) with the possibility of upwave development of multiple bar systems. Offshore bars may then play an important role in reflecting wave energy, thereby protecting beaches from the full impact of the incident waves. A change in the mean sea level (SAYLOR and HANDS, 1970) or removal of bars by dredging, for example, can lead to a sudden increase in the wave energy reaching the beach and result in flooding and erosion.

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The present paper is intended as a contribution to the understanding of the coupling between bar formation and the development of partially-standing waves over the bars.

If beach reflection gives rise to partially-standing waves outside the breaker zone, a possible mechanism for the development of sand bars is residual sediment transport by the spatially non-uniform mass-transport velocities associated with the wave field. LONGUET-HIGGINS (1953) showed, for progressive waves, that the mass transport velocity at the edge of the bottom boundary layer is in the direction of wave advance and that, for standing waves, there is a residual circulation pattern above the boundary layer, consisting of quarter-wavelength cells in which trapped fluid slowly rotates. This residual motion is upwards beneath the antinodes of surface elevation, and downwards beneath the nodes. Hence, close to the bed, its direction is from nodal to antinodal positions. Qualitatively similar results are obtained for both laminar and turbulent flows (JOHNS, 1970). The relevance of the mass-transport mechanism in the present context is that, provided the basic wave motion can entrain grains from the bed into suspension, then any residual flow present may give rise to a net movement of such grains. Beneath a pure standing wave, fine particles moving as suspended load will be transported by the residual circulation away from nodal positions towards the antinodes, where they will settle out. Thus sediment grains will tend to accumulate beneath the antinodes of elevation, forming bars spaced at half the surface wavelength. This effect has been demonstrated in the laboratory by NIELSEN (1979).

The case of a partially-standing wave system over a horizontal bed has been examined by CARTER *et al.* (1972) who determined for what values of the reflection coefficient, and under what parts of the wave envelope, the direction of mass-transport near the bed becomes opposed to the direction of the incident wave motion. They assumed that *reversal* of the near-bed mass transport velocity was a pre-requisite for bar formation. In particular, they showed that if the reflection coefficient R, defined as the ratio of the reflected to the incident wave amplitude, is greater than 0.414 then, near the bottom of the boundary layer, reversal of the mass-transport velocity occurs at a point mid-way between each antinode and the next nodal position in the direction of wave advance. They confirmed aspects of their theoretical argument by observing the behaviour of a fine sprinkling of sand, moving as bedload (within the boundary layer) on the flat base of a laboratory flume. However, they did not investigate the validity of their criterion for R in relation to bar formation, or in any cases in which short sand ripples formed on the bed. The sediment transport processes associated with vortex formation and shedding above such ripples may give rise to a direction of net sediment transport near the bed which is different from that which might be inferred from the mass-transport velocity in isolation.

Laboratory experiments involving sand-bar formation were carried out by SCOTT (1954). He described how, even in cases of low reflection when there was no reversal of mass-transport velocity near the bed, bars formed outside the breaker zone. These bars were initiated by a small amount of beach reflection and, as they grew in size, the standing wave component above them became "visible." Scott commented that the bars themselves must have caused additional reflection which built up the standing waves; in other words that there was a "coupling" between wave reflection and bar growth. BROOKE BENJAMIN *et al.* (1987) have described similar experiments in which bars were observed to form with spacings of about half the local surface wavelength. The development of the bed profile occurred in several stages, one of which was thought to be associated with a resonant interaction between the surface waves and the bed. However, in contrast to Scott, they concluded that, while the enhancement of standing waves can contribute to bar formation, this is likely to be only a comparatively minor effect.

DAVIES (1982) argued that any "coupling," or resonant interaction, of the above kind is likely to be associated with the phenomenon of Bragg reflection of incident waves by periodic disturbances (sand bars) on the bed. Bragg reflection has been well known in solid-state physics for about sixty years and, in the present context, occurs when the bar wavelength (λ_b) is one half of the (normal) incident wavelength (λ_s). The "coupling" between the waves and the bed arises because the mass-transport mechanism described above for standing waves serves to enhance any existing bars. This will give rise to increased reflection and, hence, further bar growth, and so on, until a final limiting bar profile is attained.

Bragg reflection of surface waves by (fixed) undulations on the bed has been studied extensively in recent years. DAVIES (1982) used linear perturbation theory to calculate the reflection coefficient R of a patch of long-crested bars on an otherwise flat bed. Despite the limitation of this approach to weak reflection, the theory explains the resonance in the vicinity of $\lambda_s = 2\lambda_b$, predicting a linear increase in R as the number of bars in the patch increases. It shows also, for non-resonant cases ($\lambda_s \neq 2\lambda_b$), that R is oscillatory in the ratio of the total length of the bar patch to the surface wavelength λ_s. Convincing support for this theory was obtained in a series of laboratory experiments carried out with (fixed) bars in a wave flume (DAVIES and HEATHERSHAW, 1984). With a patch of 10 bars of small amplitude, reflection coefficients of up to 80% were measured, producing dramatic partially-standing wave patterns on the up-wave side of the bars. Also, in one run in which a veneer of sand grains was sprinkled on both the flat and barred regions of the bed, the movement of grains was consistent with the growth of new bars in the up-wave direction (HEATHERSHAW and DAVIES, 1985). However, insufficient sand was present to study the phenomenon of bar growth fully.

More recent comparisons with the data of DAVIES and HEATHERSHAW (1984) have been made by MEI (1985), DALRYMPLE and KIRBY (1986) and KIRBY (1986). Comparisons based on similar laboratory experiments involving fixed beds have been reported by HARA and MEI (1987) and BROOKE BENJAMIN *et al.* (1987). Further theoretical investigations related to the present study are referred to by DAVIES *et al.* (1989).

Most of the studies cited above were concerned with fixed beds. The present paper describes laboratory experiments designed to study the development and stability of bars on a fully erodible sand bed. Attention is focussed both on the evolution of the bar patch in relation to measurements of the wave field made on its up-wave and down-wave sides, and on the detailed sediment transport processes involved in the formation of the bars. Initially, the experimental set-up is described. This is followed by an account of results obtained with two different sediment types. The specific questions addressed are:

(1) How and where do bars form under partially-standing waves?
(2) Are the bars stable features?
(3) Do bars on an erodible bed give rise to enhanced reflection of the incident waves?
(4) What factors limit the maximum bar height attained?

LABORATORY EXPERIMENTS

The experiments were carried out in a horizontal, glass-walled flume, 0.3 m wide, 0.45 m deep and 10 m long, as shown schematically in Figure 1. Waves were generated by a wedge-type wave-maker positioned at one end of the flume. This was capable of generating monochromatic waves with periods in the range 0.5–3.0 s, though in the present experiments a narrower range was used (0.9–1.3 s). The wave amplitude was controlled by setting the stroke of the wave-maker, such that amplitudes in the range 5–40 mm were obtained. At the other end of the flume, a reflecting beach was present in all the experiments. Various beach arrangements were used including an adjustable, impermeable, plane-sloping beach, a permeable wooden-slatted beach and a "natural" sand beach.

Measurements of the wave-field were made using conductivity wave gauges. Each gauge consisted of a pair of stainless-steel wires of diameter 1.5 mm and length 0.3 m, spaced 12.5 mm apart, which were partially lowered into the water. Four gauges of this type were fixed to moveable carriages mounted on rails above the flume and deployed as two gauge pairs, one at the wave-maker end of the flume and the other towards the beach. The electrical conductivity of each gauge was related linearly to its depth of immersion and hence to the wave elevation. Measurements of elevation were logged on a microcomputer incorporating an analogue-to-digital converter. The wave-field was monitored by digitising the elevation simultaneously at each gauge position for just over 40 seconds at a rate of 25 Hz. In this way, wave profiles were measured to an accuracy of one or two tenths of a millimetre. A static calibration of the gauges was carried out before each experiment. The effect of the meniscus on the gauge

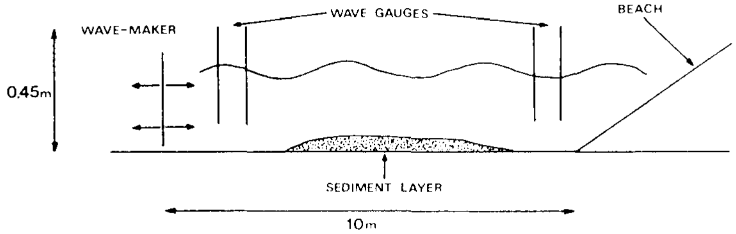

Figure 1. Schematic diagram of the experimental arrangement.

measurements was found to be unimportant in the experiments described. Full details of the wave gauge measurements are given by O'HARE (1989).

The wave period was calculated from the record of the gauge closest to the wave-maker by counting the number of digitisations between 30 zero-crossings of elevation (*i.e.* 15 wave periods). The average wave period thus obtained had an error of about 0.002 s (or about $\frac{1}{500}$th of the period). This estimate was used, together with the measured mean water depth, to calculate the surface wavelength from the dispersion equation to an accuracy of a few millimetres.

The digitised records were analysed using a Fast Fourier Transform (FFT) to obtain the amplitudes of the fundamental and first harmonic components of the wave-field. The FFT produced some spreading of the wave energy, but examination of the Fourier coefficients revealed that almost all the energy associated with the fundamental could be accounted for by taking a band of nine frequencies centered on the fundamental (as calculated from the wave period). Similarly, a band of seven frequencies accounted for the energy in the first harmonic.

Values for the amplitudes of the incident and reflected waves were obtained from the measurements of elevation made with the gauge pairs by applying the method of GODA and SUZUKI (1977). The reflection coefficient was defined as the ratio of the reflected and incident amplitudes in the vicinity of the fundamental frequency. This information was obtained (over regions of flat bed) at regular intervals (usually 5 or 10 minutes) through each experiment. Additional quantities recorded were the maximum and minimum elevations measured by each gauge during a given record, and the percentage of energy in the fundamental and first harmonic frequencies as calculated from the FFT analysis. In almost all the experiments, at least 90% of the total wave energy was in the fundamental frequency, as required for the reliable calculation of the reflection coefficient.

Two different types of sediment were used in the experiments, initially fine glass spheres ("ballotini"), and later an industrial sand. The ballotini was more nearly of a single grain size than the sand, with 60% of grains having diameters in the range 90–125 μm. The sand comprised generally larger grains (>125 μm) and had a greater spread of grain diameters. Also, the sand was more dense than the ballotini (2,670 kg/m^3 compared with 2,530 kg/m^3). Thus it was anticipated that a bed composed of ballotini would be more easily eroded than a bed composed of sand and, consequently, that the sand would provide a bed layer in which bars would be more stable. Many of the experiments were of several hours' duration, and the development of the bed was recorded both by drawing its profile on clear acetate sheets fixed to the glass wall of the flume, and also by measuring the mean bed level at regular intervals along the entire length of the flume.

EXPERIMENTAL RESULTS USING A BALLOTINI BED

To investigate the process of bar formation under a partially-standing wave system, an initial series of four experiments was performed using either the plane-sloping beach or the wooden-slatted beach. A layer of ballotini was placed over a central test section in the flume of length 5 m, with depth at the outset of each experiment approximately equal to 25 mm. Wave measurements were made with gauge pairs situated above the regions of flat bed both up-wave of this test section towards the wave-maker, and between the test section and the beach. The beach provided the initial reflected wave component needed to trigger the formation of the bars. A full description of these experiments is given by O'HARE (1989).

The evolution of the bed profile took place in several stages. Initially small-scale ripples formed with wavelengths of about 30–50 mm, related to the *local* amplitudes of the horizontal excursions of the water particles near the bed. The ripples formed first beneath the nodal positions of the wave envelope (where the water particle excursions were greatest), and then gradually spread (over a period of 10–20 minutes) to cover the entire bed. These ripples produced vortices which lifted grains off the bed resulting in a layer of suspended sediment some 20–30 mm in height. This suspension was most pronounced where the oscillation of the fluid particles was greatest (*i.e.*, beneath the nodes).

In general, sediment motion above rippled beds depends upon the process of vortex formation and shedding in each wave half-cycle (SLEATH, 1984). Flow above the stoss slope of the ripple causes a jet of sediment to be entrained from the crest. Most of this sediment is trapped in the vortex above the lee slope, but some is carried on to the stoss slope of the next ripple. On flow reversal, the strong lee vortex lifts the trapped sediment from the bed as it is pushed back over the crest. During this process sediment may be lifted to a height of one or two ripple wavelengths above the ripple crests. The suspended sediment then either settles back to the bed or is resuspended by subsequent vortices.

In the present partially-standing wave system, suspended sediment grains were carried from positions beneath the nodes of the wave envelope towards positions beneath the antinodes, by the residual mass-transport circulation described earlier. Thus, over a period of several hours, bars were formed with spacings equal to half the local surface wavelength, and with their crests beneath the antinodes of surface elevation. These bars were of small amplitude compared with the mean water depth over the ballotini layer, typically having a ratio of maximum bar amplitude (b) to mean water depth (h) of the order of 0.05. Bars of this size were too small to interact significantly with the surface wave and bring about major changes in the wave-field. (Results from DAVIES and HEATHERSHAW (1984) indicate that a ratio of $b/h > 0.1$ is necessary before significant reflection is produced by a bar patch). The fact that only modest bar heights were attained was probably due to the easily erodible nature of the ballotini bed, so that only a short period of changed wave conditions was required to erode an established bar patch. Small changes in the generated surface wavelength (of the order of 20 mm) often occurred. These were probably due to interactions between the reflected wave and the wave-maker, and also to slight irregularity in the performance of the wave-maker. Even such small changes in the wavelength, when compounded over the entire bar patch, were capable of producing a significant mismatch between the surface wavelength and the resonant Bragg wavelength of the bars.

Despite the fact that only small bars were formed in each of the runs with the ballotini bed, there was some evidence that increased reflection of the incident wave occurred during the process of initial bar formation. For example, Figure 2 shows the time series measured during a run (Experiment C4) in which seven bars with a maximum ratio of $b/h = 0.07$ were formed. The main parameters for this experiment are quoted in Table 1. During an initial period of about 10 minutes, the wave-field stabilised as the bed roughness increased. Following this, the incident amplitudes measured up-wave of the ballotini patch and towards the beach both followed a nearly identical pattern of variation brought about by small changes in the incident wavelength. At the beach, the reflected amplitude fell slowly as the amount of wave energy arriving at the beach decreased (as bars formed). Up-wave of the patch the reflected amplitude rose by 10% over the first 180 minutes of the experiment as bars formed and enhanced the reflection. The associated reflection coefficient up-wave of the bars increased from around 0.25 at the start of the experiment to about 0.28 after 180 minutes, while the beach reflection remained constant at about 0.32. It is the *increase* in the reflection coefficient on the up-wave side of the bars which is significant here. The fact that the beach reflection coefficient was larger than that measured on the up-wave side is explained by the effects of frictional dissipation at the bed and side-walls of

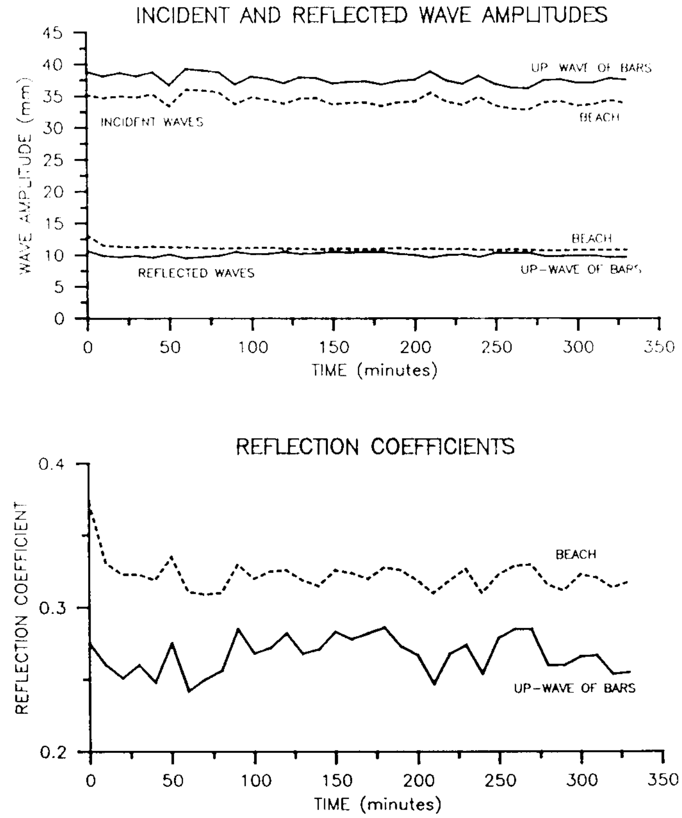

Figure 2. Time series of incident and reflected wave amplitudes and reflection coefficients measured during Experiment C4.

Table 1. *Experimental parameters: The figures for the wave amplitude and percentage energies in the fundamental and first harmonic frequencies are averages over the entire length of the run. The low percentage energy in the fundamental measured during Experiment D5 was caused by a period of wave breaking and instability during the run. The wavelengths were measured upwave of the sand patch on a region of flat bed.*

Experiment	C4	D2	D11	D12	D5
Sediment Type	Ballotini	Sand	Sand	Sand	Sand
Beach Type	Slatted	Slatted	Plane	Plane	Sand
Water Depth (m)	0.250	0.170	0.175	0.173	0.094
Wavelength (m)	1.830	1.269	1.195	1.391	0.836
Amplitude (mm)	37.6	27.8	21.1	17.3	14.0
Fundamental (%)	91.2	86.2	91.1	96.8	70.0
1st Harmonic (%)	3.6	7.9	5.6	2.5	14.0
Number of Bars	7	8	8	7	13
b/h Ratio	0.07	0.06	0.1	0.12	0.15

the flume. In a hypothetical case in which, for example, the beach reflection coefficient was 0.33 and the waves were attenuated by 5% of their amplitude per wavelength (a typical value), then the reflection coefficient up-wave of the bars would be approximately 0.2, that is 60% of the beach reflection coefficient. This was confirmed by additional experiments which investigated the attenuation of waves in the flume.

After 180 minutes, the reflected amplitude up-wave of the bars began to fall rapidly to its original value, this change occurring at the same time as an abrupt decrease by at least 10 mm in the surface wavelength. The effect of this shift in the wavelength was sufficient to move the standing wave pattern relative to the bars, so that erosion and deposition no longer acted to cause bar growth.

One additional point of interest is that apparently stable bars were observed to form even when the initial beach reflection coefficient was as low as 0.2. This contradicts the argument of CARTER *et al.* (1972) who quote a lower limit on the beach reflection coefficient for stable bar formation of 0.414, based on the requirement of a *reversal* of the mass transport at certain positions along the bed. It would appear from the present observations that even small *spatial periodicity* in the mass transport close to the bed is a sufficient condition for the initiation of bar formation.

EXPERIMENTAL RESULTS USING A SAND BED

A series of twelve closely similar experiments was performed with a layer of sand replacing the ballotini (see O'HARE, 1989). It was expected that the sand would provide a less erodible bed layer and, consequently, would result in more permanent bedforms. It was also anticipated that the known variation in grain sizes would be an important factor in stabilising any bars formed. As in the runs with the ballotini bed, the formation of small-scale ripples on the initially flat sand bed was an important prerequisite for bar evolution. However, with the sand bed, there was less suspension of sediment grains as a result of vortex shedding.

Sand bars were observed to form approximately mid-way between the nodes and antinodes of surface elevation, with most suspension occurring above the crests of the bars. This suggests that asymmetry in the strengths of the vortices shed from the rippled bed in successive wave half-cycles played an important role in the formation of bars, since the mass-transport circulation acting alone on sediment in suspension would have resulted in bar-crest formation *close to the antinodes* (as found in the experiments with ballotini).

If an asymmetry exists between the strengths of the vortices shed from the bed in consecutive wave half-cycles, then there will be a net movement of sediment. Potentially, forward mass transport close to the bed will lead to the formation of asymmetrical ripple profiles and result in different amounts of sediment movement in each wave half-cycle. In the first half-cycle, during the passage of the wave crest, coarser sediment will be moved forward as bedload by the strong surface layer "flow," while some fine material may be moved forward as suspended load by the relatively weak stoss-vortex formed by the passage of the previous trough. In the second half-cycle, when the flow reverses, the surface flow is weaker, but the shedding of a strong lee vortex results in the backward movement of a substantial amount of sediment in suspension. Thus during the passage of the wave crest, the predominant mechanism of sediment transport is the forward movement of both coarse and fine grains by the surface flow (bedload), whereas during the passage of the wave trough, finer sediment grains are carried backwards in suspension by the lee-vortex. Hence, when a mixture of grain sizes is present, the motion of at least the finer sediment grains can be opposite to the direction of the near bed mass transport. Consequently, bar crests may form at any position relative to the nodes and antinodes of surface elevation depending upon the proportions of coarse and fine grains present.

Although in most experiments the bars only reached amplitude to depth ratios of $b/h \approx 0.05$, in some runs b/h attained values of up to 0.15. In some of these latter runs coarser grains of sand tended to accumulate in the vicinity of the bar crests (beneath a surface veneer of mobile fine grains). This is consistent with the observations of SCOTT (1954) who described sandbar formation even in cases of low reflection (when there was no reversal of mass transport near the bed). The following explanation for this distribution of sediment seems likely. Asymmetry in the strengths of ripple vortices tended to result in the forward movement of coarser grains as bedload and the backward movement of finer grains as suspended load. Close to the nodes of surface elevation, where the horizontal oscillatory motion of water particles was greatest and the forward transport of bedload material was interrupted, more of the coarse grains were lifted into suspension and carried backwards, so that the forward migration of these grains was arrested as they moved towards a node. Thus coarse grains of sand tended to accumulate near the nodal positions of surface elevation forming bars, while the finer grains moved towards the antinodal positions. The coarse grains were more resistant to erosion by the higher shear stresses experienced at the bar crests than finer grains, and so the presence of these grains was an important factor in stabilising the bars.

In all cases the development of bars increased the reflection of the incident wave. Figure 3 shows the reflection coefficient measured up-wave of a patch of about eight bars with a final equilibrium value of $b/h \approx 0.06$ (Experiment D2—see Table 1 for experimental parameters). Over the first 125 minutes of the experiment, the reflection coefficient up-wave of the bars increased by 50% from 0.18 to 0.27. As expected, the enhancement of the standing wave component was more pronounced than this when b/h was larger. Figure 3 also shows the reflection coefficient measured up-wave of a patch of eight bars with an equilibrium value of $b/h \approx 0.1$ (Experiment D11). In this case the reflection coefficient doubled from 0.11 initially, to about 0.22 after 200 minutes.

In general, the bar profiles and surface waves were observed to reach an equilibrium state, further growth of the bars being inhibited by increased erosion from the bar crests and by gravitational forces limiting the slope of the bars. Figure 4 shows the time series for a run (Experiment D12) in which an equilibrium was attained after about 400 minutes and then maintained for a further 400 minutes. Seven bars were formed in this run with an average wavelength of about 0.6 m, with $b/h \approx 0.12$ and a maximum final steepness (bar slope) of about 0.07 (see Figure 5a). The formation of these bars gave rise to an increase in the reflection coefficient up-wave of the bars from about 0.25 initially, to nearly 0.50 at equilibrium. (The surface wavelength over the bars was reduced from the value quoted in Table 1 to around 1.25 m due to the reduction in the mean water depth over the sand patch). The beach reflection coefficient also increased during the run, but this rise may be attributed to a decreasing incident wave amplitude at the beach due to the growth of the bars, which resulted in slightly changed wave breaking conditions.

In a number of runs in which large bars were formed, the reduction in the local water depth over the bar crests led to wave breaking. This caused large regions of turbulence and led to rapid erosion of the bars. Figure 6 shows the time series for such an run (Experiment D5). The reflection measured at the beach was fairly constant throughout the experiment, whereas the reflection on the up-wave side of the bars

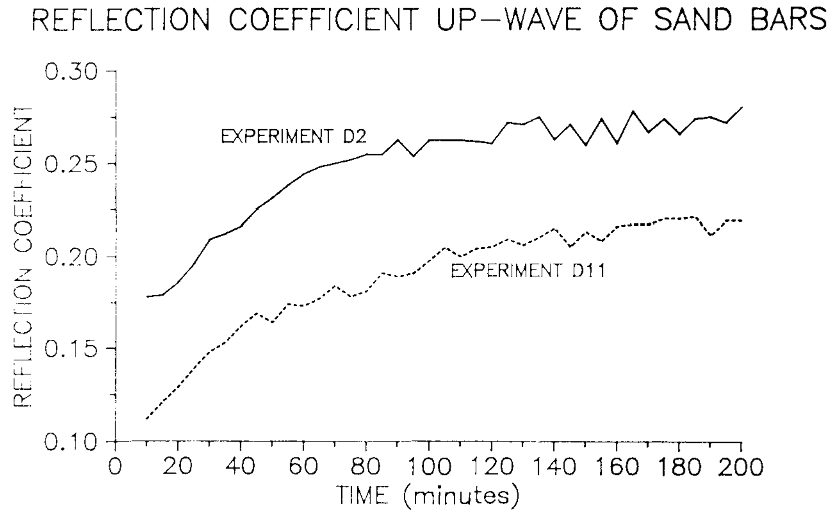

Figure 3. Time series of reflection coefficient measured up-wave of sand bars during Experiments D2 and D11.

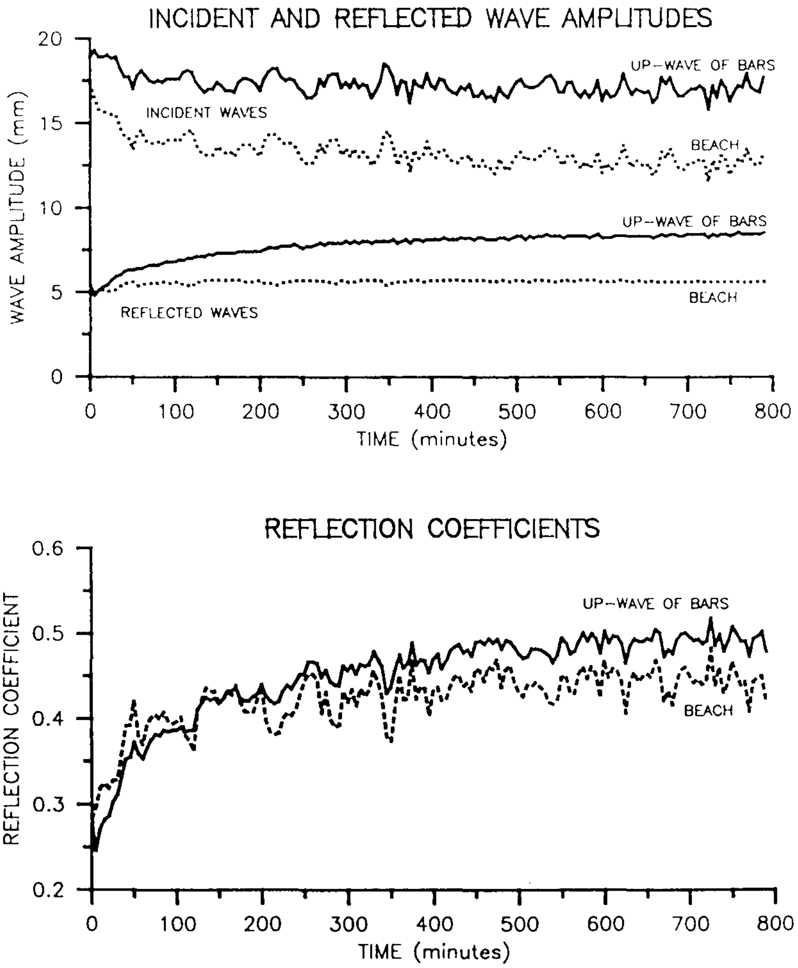

Figure 4. Time series of incident and reflected wave amplitudes and reflection coefficients measured during Experiment D12.

increased dramatically from about 0.1 to 0.5 in only 30 minutes. About 12 bars with $b/h \approx 0.15$ were formed during this time, the wave-field becoming visibly more standing in nature up-wave of the bar patch than near the beach. However, after 30 minutes of the run, the reflection coefficient on the up-wave side of the bars fell sharply, due to wave breaking over the bar crests where the water depth was only about 0.06 m (the initial flat-bed water depth being 0.09 m). Harmonic analysis of the associated wave records confirmed that energy was lost from both the fundamental and first harmonic frequencies, with the average percentage energy in the fundamental frequency, measured down-wave of the bars, falling from about 85% initially to just over 40% during the period of wave breaking. This was consistent with the observed wave breaking and explains the variation in the incident amplitude measured down-wave of the test section. The bars that had been formed were quickly eroded and flattened out by the non-linear wave-field, until the bed and surface wave conditions were much the same as at the start of the experiment. Once the original bars had been removed, the wave-field became more stable and, at 90 minutes from the start of the run, new bars began to form, again leading to higher reflection coefficients at the wave-maker end of the flume. However, in this second period of bar formation, the waves, while showing signs of instability and break-

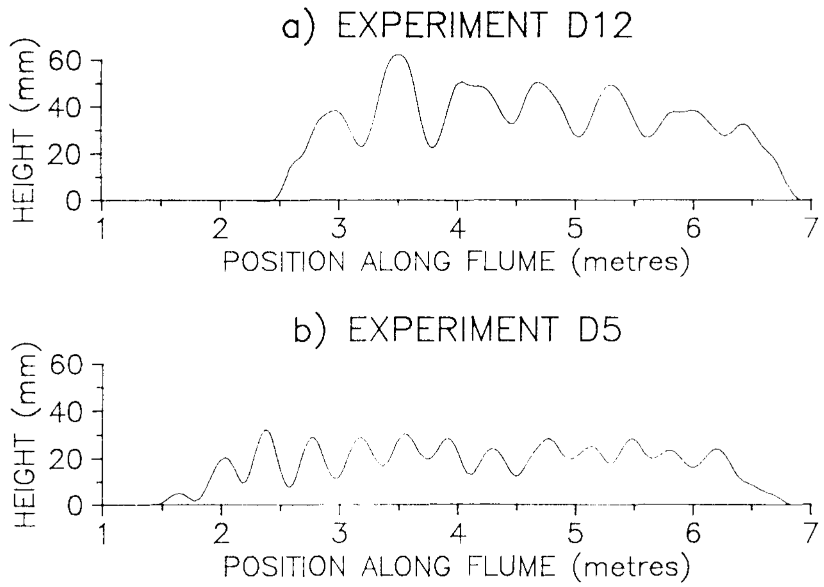

Figure 5. Final bed profiles from (a) Experiment D12 and (b) Experiment D5.

ing, did not produce the same erosion of the bar patch. Instead, an equilibrium was attained between the waves and the bed. The final bed profile in Figure 5b shows a patch of 13 bars with an average wavelength of 0.4 m, with b/h $\approx$ 0.15 and a maximum final steepness of about 0.06. (In this case the surface wavelength over the bars was reduced to around 0.8 m by the reduction in mean water depth). It appeared that there was a very fine dividing line between stable conditions in which bars formed and existed in equilibrium with the surface wavefield, and unstable conditions in which the bars were eroded by breaking waves. It is possible that the bars formed initially were unstable because insufficient large grains had migrated to the crests in order to stabilise the bars when wave breaking occurred.

Sudden changes in sand bar profiles have been reported by BROOKE BENJAMIN *et al.* (1987). They noted in their laboratory experiments that, as the bed evolved, there were periods of 15–30 minutes during which the bed profile underwent major changes, followed by comparatively long periods of 25–30 hours during which the profile changed only slightly and a process entailing quasi-resonant reflection was probably operative. Over this period of hours the standing wave component of the motion grew until, eventually, wave breaking generated large turbulent zones which caused rapid changes in the bed profile.

DISCUSSION

Comparison of the results obtained with the beds of sand and ballotini indicates that the positions of the bar crests and troughs relative to the nodes and antinodes of surface elevation depended on the grain size characteristics of the sediment. There were two observed modes of sediment transport: suspended load, and movement of sediment near the bed associated with vortex shedding from small-scale ripples. Of these, the latter was more important at lower reflection coefficients and when a mixture of grain sizes was present. The net transport rate and direction depended upon the sediment grain size. By comparison, any grains in suspension, which had a net motion resulting from the mass-transport circulation cells associated with the partially-standing waves, tended to converge towards the antinodes of surface elevation.

In general, for bars to form with crests beneath the antinodes, the shear stresses acting on the bed must be everywhere above the threshold of sediment motion, or at least suffi-

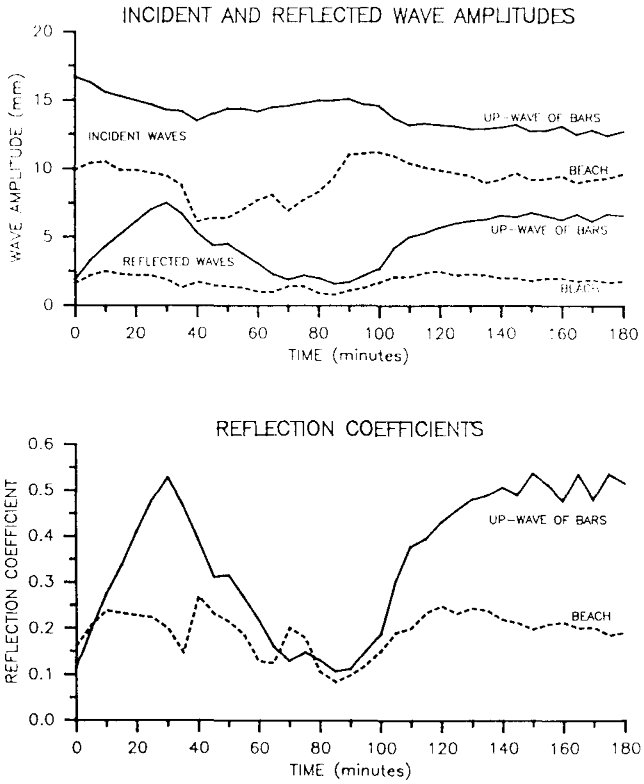

Figure 6. Time series of incident and reflected wave amplitudes and reflection coefficients measured during Experiment D5.

cient to prevent sediment grains from settling to the bed before they reach the antinodes. For the ballotini bed, it was concluded that the residual mass-transport circulation was the mechanism responsible for the net movement of grains in suspension and, hence, the growth of bars beneath antinodal positions. The experiments with sand produced results quite different from those with ballotini. Bar crests formed mid-way between the nodes and antinodes, whatever the value of the reflection coefficient. In principle, differential movement of coarse and fine grains as a result of asymmetry of ripple vortices, coupled with some net suspended sediment transport due to the residual circulation, could result in bar crests forming in a variety of positions under the partially standing wave envelope, depending upon the mixture of grain sizes. The presence of coarser grains at the bar crests may have been an important factor in stabilising the bars, these grains being more resistant to erosion.

Once the bars were sufficiently well developed, Bragg reflection of the surface waves led to increased reflection coefficients up-wave of the bar patch. In most cases the increase was by a factor of between 1.5 and 2, but the low starting values meant that the maximum reflection coefficients attained were still fairly small (less than 0.5). However, in some of the runs, when large bars were formed, the reflection coefficients up-wave of the bar patch increased by factors of 5 or 6 as the experiment progressed, so that quite dramatic standing wave components and significant protection of the beach by the bars was observed. In these cases there were at least ten bars with a ratio of bar amplitude to water depth in excess of 0.1.

It proved difficult to generate large bars during the experiments for a number of reasons. In the first place, surface waves of relatively large amplitude were required to produce sediment movement on the bed, and such waves were inherently unstable. In particular, as the bars grew in height, the reduction in the local water depth over the bar crests tended to make the wave-field unstable, eventually leading to wave breaking and the rapid erosion and flattening of the bed. In this way, wave breaking imposed an upper limit on the maximum bar height (and hence the maximum reflection) obtained.

In many of the experiments a quasi-steady state was reached in which the bars and wave-field existed in equilibrium. In these cases it appeared that further increases in the bar height were inhibited by enhanced sediment mobility at the bar crests; sediment grains at the crests, being higher in the flow, were more readily erodible by the high shear stresses experienced, and also the bars were subject to increasing gravitational forces tending to flatten the bed. The maximum bar steepnesses obtained were about 0.07.

The formation of larger bars in the experiments with sand compared to those with ballotini suggests that the existence of a *mixture* of sediment grain sizes is an important factor both in the formation of bars and in their subsequent stability. Further to the results presented in this paper, initial observations of the development of bars in sand taken from Lligwy beach in North Wales appear to support this suggestion. The sand in question was much more variable in size and shape than that used for the present study and contained a large amount of coarse, shelly material. Pronounced bars were formed with crests between the nodes and antinodes, and with accumulations of lighter-coloured shelly material clearly visible at the bar crests. These bars led to significant reflections and quite dramatic standing wave components up-wave of the bar patch.

Although the experiments performed in this study were for a horizontally one-dimensional flow and monochromatic surface waves, many of the results are readily applicable to the situation on a real beach. However, in the field, bars generally form with spacings too great (of order 100 m) to be associated with wind waves and swell of the kind readily observed. Instead, they are very probably associated with the reflection of long waves produced by the group structure of incident waves (BOWEN, 1980). It is believed that the partially-standing waves which result from the reflection of these long waves at the shoreline, either set up a slow residual mass transport circulation or bring about a small asymmetry in ripple vortices, the effect in either case being to initiate sand bar formation. The importance of the shorter carrier waves is that they mobilise the bottom sediments by creating stresses on the bed which are above the threshold of sediment motion. In laboratory experiments with monochromatic waves, the surface wave plays the role both of the long standing wave component (which may control the *net* distribution of sediment) and of the shorter surface waves (which bring about the sediment movement itself). Thus it is important to appreciate that results such as the measured bar spacings, positions of the bar crests and troughs relative to the surface wave-field and shifts in the surface wavelength are likely to be associated, in the field, with the long standing wave component.

CONCLUSIONS

The evolution of sand bars has been observed in the laboratory under partially-standing waves. Bars formed with spacings equal to half the surface wavelength, the positions of bar crests and troughs relative to the nodes and antinodes of surface elevation depending upon the mixture of grain sizes present and the energetics of the flow. In the present experiments, the sediment transport mechanisms responsible for bar formation were linked to the residual mass-transport circulation beneath the partially-standing waves, and to vortex formation and shedding above small-scale ripples on the bed.

The presence of bars led to increased reflection coefficients up-wave of the bar patch. Significant additional reflection occurred when the ratio of the bar amplitude to the mean water depth exceeded 0.1, supporting the argument that a coupling exists between bar growth and the resonant (Bragg) reflection of incident waves. Bars on an erodible bed were stable features with the presence of coarse grains at the bar crests being an important stabilising factor. The maximum bar height was limited by increased erosion of sediment grains at the bar crests due to increased shear stresses, and by gravitational forces acting on the grains which limited the slope of the bars. The maximum bar steepness was about 0.07. In addition, wave breaking imposed a dramatic limitation on the maximum bar size.

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☐ RÉSUMÉ ☐

Rend compte d'une série d'expériences menée en canal à houle de 10 m de long pour étudier le développement et la stabilité des barres. La formation d'une barre débute sous l'action d'une houle monochromatique engendrée par une batteur à une extrêmité du canal et partiellement réfléchie par une plage située à son autre extrêmité. Les granulats s'accumulent en barres dont l'espacement correspond à la moitié de la longueur d'onde locale de la houle en surface. La position des barres par rapport aux noeuds et antinoeuds de l'enveloppe de la houle dépendent du type de sédiment utilisé. La taille des barres croît avec le coefficient de réflexion mesuré sur le côté haut de la vague: cela suggère un couplage entre la croissance de la barre et la réflexion résonnante des ondes incidentes. Dans plusieurs expériences, on a obtenu un équilibre du profil des barres, dans d'autres, le champ de vagues est devenu instable avec un déferlement produit juste au dessus de la crête de la barre qui s'aplanit. On a identifié deux modes de transport: un mouvement de particules fines en suspension par le transport de masse résiduel associé au champ de houle stationnaire; un mouvement de particules fines et grossières par la formation d'un vortex et une déchirure au dessus des petites rides de sable. Lorsque le transport net est tel que les grains les plus grossiers s'accumulent sur les crêtes des barres, cela les stabilise.—*Catherine Bressolier (Géomorphologie EPHE, Montrouge, France).*

RESUMEN

Se ha realizado una serie de ensayos en un canal de 10 m de largo para estudiar la estabilidad de barras de arena. La formación de la barra se inició mediante trenes de ondas monocromáticos. Los granos de sedimento se acumulaban en la barra en una separación del orden de la mitad de la longitud de onda local. La posición de la barra en relación con los nodos y antinodos dependía del tipo de sedimentos. Al crecer la barra el coeficiente de reflexión creció significativamente sugiriendo un acoplamiento entre el crecimiento de la barra y la reflexión resonante (Bragg) de la onda incidente. En algunos ensayos se obtuvieron perfiles de barra en equilibrio. Sin embargo, en otros la rotura de la ola provocaba el aplanamiento de la barra. Se ha identificado dos modos de transporte: transporte de granos finos por la circulación del transporte de masa residual asociado con el movimiento parcialmente estacionario y el movimiento de granos gruesos y finos por formación y emisión de vórtices sobre los ripples de pequeña escala. Cuando el transporte neto era tal que los granos gruesos se acumulaban en la barra, se producía una estabilización de la misma.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

ZUSAMMENFASSUNG

Eine Reihe von Experimenten wurde in der zentralen Teststrecke eines 10m langen Wellenkanals durchgeführt, um die Entwicklung und Stabilität von Sandbänken zu untersuchen. Die Barrenbildung wurde durch (monochromatische) Wellen ausgelöst, die von einem Wellengenerator an einem Ende des Kanals erzeugt und teilweise von einem sich am anderen Ende befindenden Strand reflektiert wurden. Sedimentkörner akkumulierten sich zu Sandbänken, deren Abstände zueinander der halben Wellenlänge der jeweiligen Oberflächenwelle entsprach. Die Lage der Barren in Bezug auf die Knoten und Gegenknoten der Hüllwellen hing von dem verwandten Sedimenttyp ab. Wuchsen die Sandbänke an, so vergrößerte sich der auf ihrer wellenwärtigen Seite gemessene Reflexionskoeffizient signifikant, was für eine Kopplung zwischen dem Wachstum der Barre und der resonanten (Bragg) Reflexion der auftreffenden Welle spricht. In einigen Experimenten wurden bei den Sandbänken stabile Gleichgewichtsprofile erreicht. Dagegen wurde in anderen das Wellenfeld unstabil, indem sich Wellen auf den Barrenkämmen brachen, was zu einer Verflachung führte. Zwei Arten des Sedimenttransports wurden identifiziert: (a) die Bewegung feiner Korngrößen in Suspension durch die Restzirkulation des Massentransportes, die mit einem teilweise stehenden Wellenfeld verbunden ist, und (b) die Bewegung sowohl grober als auch feiner Korngrößen durch Strudelbildung und die Verbreitung kleinräumiger Rippeln im Experimentbecken. Wenn der Nettotransport so war, daß gröbere Körner sich auf den Kämmen der Sandbänke akkumulierten, so hatte dies für die Sandbänke eine stabilisierende Wirkung.—*Helmut Brückner, Geographisches Institut, Universität Düsseldorf, F.R.G.*