ABSTRACT: Experimental investigation of subaqueous bed forms has been undertaken and analyzed. Based upon already-existing theories in the area of sediment bed-form initiation and development, 7 experimental runs were carried out in a 440 mm-wide, glass-sided, 12 m-long laboratory flume. For each run, bed profiles were measured at 30 sec intervals. The sediment in use was a fine sand with $d_{50} = 0.2$ mm. The study is the first of a series of studies looking at the phenomenon of submerged sediment bed-form behaviour. The main purpose of the study was to gain information on the relations central to linkages between bed-form propagation speed, sediment-transport rate and predictions of bed development. Relations predicting equilibrium sandform speeds as functions of flow conditions and sediments are available in the literature, although these relations have not been widely tested. More general relations predicting sand-form speeds as functions of flow conditions, sediments, and bed-form magnitudes remain to be determined.

1 INTRODUCTION

1.1 Bed-form movement and sediment transport

For any sediment bed form propagating steadily without changing size or shape, sediment continuity considerations readily lead to $q_{SH} = cH$, where $q_{SH}$ is the volume rate of sediment transport over the crest of the bed feature per unit width of channel, $c =$ bed-form celerity and $H =$ bed-form height measured crest to subsequent trough (e.g., Coleman and Melville, 1994). Depending on how sediment volume is measured, this can also be expressed as $q_{SST} = cH(1-p)$ for equilibrium or slowly-growing subaqueous bed forms (Nino et al., 2002), where $p$ is the porosity of the deposited sediments.

A relation, such as that above, between sediment transport and the magnitudes and speeds of propagating discrete bed forms (ripples and dunes) is potentially very useful. If sediment is transported as bed load in the form of bed forms, measurements or predictions of bed-form magnitudes and celerities as these waves develop, facilitate estimation of sediment-transport rates for the developing bed (as well as equilibrium bed-form transport rates). Such estimations increasingly underpredict transport rates as the proportion of transport bypassing bed-form lee faces, e.g. as suspended load, increases for stronger flows. Mohrig and Smith (1996) provide a method for estimating the bypassing fraction (up to 60%), whereby measurements or predictions of bed-form magnitudes and speeds can be used to estimate sediment-transport rates generally, and not just where sediment in motion remains cycling within individual bed forms.

1.2 Sandwave initiation theories

Different theories exist about the initiation of sandwave development. Kennedy (1969) led the stability theory approach with his irrotational flow analysis. Coleman and Fenton (2000) showed, however, that the theory of irrotational flow is inadequate for sandwave generation. Coleman and Eling (2000) further showed that bed forms have their genesis in wavelets (small scale sediment waves, which are primarily a function of sediment size and not flow characteristics).

Raudkivi (1983) proposes that sandwave initiation occurs through streamline oscillations within high-shear and constant velocity zones within the flow profile.

Other researchers, among them Nezu and Nagakawa (1993), conclude that grain entrainment and sandwave initiation are caused by the flow’s coherent turbulent structure, which interacts with the bed surface.

The range of analyses and conjecture reflects the current lack of understanding of the phenomena controlling sediment-wave generation, such phenomena potentially including grain movements, flow-bed instabilities and bed-wave interactions.

2 SANDWAVES

2.1 Classification of sandwaves

ASCE (1966) faced the problem of dividing sandwaves into ripples and dunes. The criteria for the distinction are still controversial, especially when a possible transition from ripples to dunes or vice versa occurs. The
cause and behaviour of this transition is of great interest, but up to now the behaviours of, and transitions between, these different kinds of sandwaves remain unclear. Widely-accepted classifications of ripples and dunes, with their associated characteristics, are fundamental for this research and are summarized in the next two sections. One aim of the present research is to further investigate distinctions between ripples and dunes as bed forms.

2.2 Ripples

According to ASCE (1966), ripples are small finesediment bed waves, which do not influence the water surface (Fig. 1).

It is widely accepted that ripples are small triangular sandwaves that are usually longer than 0.06 m and shorter than 0.6 m, and are restricted to sands finer than 0.6 mm. McLean (1990) states that ripples display wavelengths of the order of 0.1–0.2 m and heights of 0.01–0.02 m.

Furthermore, the theory was introduced that small-scale ripples may exist on an otherwise flat bed or may be superimposed on the stoss sides of larger bed forms. It remains unclear, however, what makes these superimposed bed forms ripples, and not dunes growing in between larger dunes, especially for sediments of \( d_{50} > 0.6 \) mm.

In line with the superimposed bed forms being ripples, Raudkivi (1997) observes that rippleforming conditions can occur downstream of the reattachment point of the surface of separation for an upstream dune crest, i.e. where the bed-shear stress is low. Yalin (1992) concludes that ripples are due to the viscous structures at the bed, defining ripples as the bed forms ‘imprinted’ by the viscous flow structures (undulations) at the bed of a nevertheless turbulent flow.

2.3 Dunes

Dunes (Fig. 2) are bed waves that occupy a significant portion of the flow depth, causing the water surface to be disturbed.

Hydrodynamically, they affect the flow with topographic accelerations and decelerations of the flow field extending all the way to the free surface (Maddux (2002)).

Dunes are normally larger and more two-dimensional features when compared to ripples. On beds of coarser uniform-grains (in general it is assumed for sediment grain sizes \( > 0.6 \) mm) only dune-like features develop. According to Bass (1993), no dunes form with sand finer than 0.15 mm. Dunes are generally restricted to sand-like sediment, but can occasionally also occur with coarser uniform-grained materials. Dunes are irregular sandwaves.

The longitudinal profile is roughly triangular, with a mild and slightly curved upstream surface, where as the downstream slope can be taken to be equal to the dynamic angle of repose \( \phi \) of the sediment.

3 EXPERIMENTAL INVESTIGATION

3.1 Experimental arrangements

Seven experiments were carried out, concentrating on sandwave development for different flows. Some of the runs reached equilibrium stages, for others recording was stopped before equilibrium. Table 1 shows an overview of the experimental runs.

The experiments were conducted in a 12 m-long, 0.38 m-deep and 0.44 m-wide glass-sided openchannel flume. Water is recirculated, as well as the sediment. On the rails of the flume, a carriage carries a depth sounding probe. The carriage traveled over a distance of 4–7 m, depending on the characteristics of the runs. For the first experiments, the carriage was moved manually downstream and upstream. For the later experiments, the carriage was motorized, making more efficient use of the equipment and time.

Before each run, the slope of the flume and the temperature of the water were measured and recorded. The velocity profile for each pump setting and equilibrium bed profile were also measured.
Table 1. Overview of conducted runs.

<table>
<thead>
<tr>
<th>Run</th>
<th>Pump Setting</th>
<th>Duration [h:m:s]</th>
<th>Equilibrium</th>
<th>U [m/s]</th>
<th>Fr</th>
<th>Re [×10^3]</th>
<th>U* [m/s]</th>
<th>θ [°]</th>
<th>Re* [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>13</td>
<td>2:02:00</td>
<td>no</td>
<td>0.3850</td>
<td>0.2621</td>
<td>1179</td>
<td>0.0302</td>
<td>0.2825</td>
<td>6.1723</td>
</tr>
<tr>
<td>D1</td>
<td>21</td>
<td>4:41:59</td>
<td>yes</td>
<td>0.6570</td>
<td>0.4472</td>
<td>2012</td>
<td>0.0673</td>
<td>1.4003</td>
<td>13.7430</td>
</tr>
<tr>
<td>RD1</td>
<td>13→21</td>
<td>3:10:45</td>
<td>yes</td>
<td>0.6570</td>
<td>0.4472</td>
<td>2012</td>
<td>0.0673</td>
<td>1.4003</td>
<td>13.7430</td>
</tr>
<tr>
<td>R2</td>
<td>10</td>
<td>1:20:41</td>
<td>no</td>
<td>0.2530</td>
<td>0.1722</td>
<td>775</td>
<td>0.0214</td>
<td>0.1409</td>
<td>4.3595</td>
</tr>
<tr>
<td>R/D3</td>
<td>18</td>
<td>1:58:43</td>
<td>no</td>
<td>0.5170</td>
<td>0.3519</td>
<td>1583</td>
<td>0.0582</td>
<td>1.0461</td>
<td>11.8783</td>
</tr>
<tr>
<td>R4</td>
<td>10</td>
<td>3:12:36</td>
<td>yes</td>
<td>0.2530</td>
<td>0.1722</td>
<td>775</td>
<td>0.0214</td>
<td>0.1409</td>
<td>4.3595</td>
</tr>
<tr>
<td>RD2</td>
<td>10→21</td>
<td>6:30:23</td>
<td>yes</td>
<td>0.6570</td>
<td>0.4472</td>
<td>2012</td>
<td>0.0673</td>
<td>1.4003</td>
<td>13.7430</td>
</tr>
</tbody>
</table>


Note: fine to medium sand with d_{50} = 0.2 mm and d_{90} = 0.28 mm, ν = 0.9798; μ = 0.000001; u_c = 0.0115; S = 0.001; τ = 21°; s = 2.65; h = 0.22 m; m = 0.75 m

Prior to each run, the sediment bed was flattened and the depth-sounding probe was fixed on the carriage. The technique behind the depth-sounding system is based on Coleman (1997), and has since been further improved at The University of Auckland. The depth-sounding system was used to record the profiles of the developing bed. According to Coleman (1997) the accuracy of bed elevation measurement is ±0.4 mm. The distance along the flume was measured using a potentiometer mounted on a 0.199 m diameter wheel running down the outside of the flume side-wall. The streamwise position was recorded at 2.45 mm distance increments, accuracy of measurement being ±1.23 mm.

For each experimental run, measurements were taken at the centreline of the flume. Therefore, only two-dimensional data evaluation can be carried out.

Bed profiles were recorded initially every 30 sec for a run, with profiles in the latter stages of the experiments recorded every 5 to 15 min.

3.2 Range of experiments
As seen from Table 1, flows were chosen for the different experimental runs based on the abovementioned sandwave theories, where distinctions are made between ripples and dunes. The chosen sediment for all the runs is a fine sand with d_{50} = 0.2 mm. This sand was chosen to ensure the development of both ripples and dunes. Therefore, one can study the differences in subaqueous sandwave initiation and development to equilibrium state for the two types of bed forms.

Bed-form development started for five runs from flat bed conditions and for two runs, the transition from ripple to dune beds was studied.

Figure 3 shows the classification of the flows and bed configurations according to van Rijn (1984). For four runs (refer to Table 1) the bed forms reached equilibrium magnitudes.

4 BED-FORM DATA ANALYSIS
4.1 General remarks
For each run, the mean (depth-averaged) fluid velocity U, and the bed shear velocity u* were determined from the measured centreline flow velocity profile (see Table 1).

Analysis of the different experimental runs according to Coleman (1996) indicated the bed-form results to be in line with previous research. The writers then focused on a more detailed and explicit analysis of...
aspects of bed forms instead of a general and traditional study. A principal goal was to gain enough information to formulate an automatic means of analyzing the development of subaqueous sediment waves. In the past, most of the analysis has been done with a large manual work load and automated analyses were often distorted because of simple determinations of wave height and length, which provide the basis for all submerged sediment wave analyses.

Therefore, this paper will focus on explicit parts of run R/D3, with special attention given to relations central to linkages between bed-form propagation speed, as a function of flow, sediment and bed-form parameters; sediment-transport rate as a function of bed-form speed and bed-form height; and the degree to which bed-form geometry can be taken to be similar. The considerations in the analyses presented here will help to provide means of automating the evaluation of the development of subaqueous sediment waves in the future and will show where there are major inconsistencies in these analyses to date.

4.2 Bed-form development of run R/D3

Run R/D3 started from flat bed conditions, with bed profiles recorded for 2 hrs. Bed profiles for the first 10 min are shown in Figure 4.

One can see from Figure 4 that the initiation of bed forms can be a sudden uniform phenomena (see bed forms 10:20:14 AM and 10:20:44 AM in Figure 5). Therefore any role of stochastic turbulence in bed-form generation, as discussed in Section 1.2, must be questioned.

The bed-form unification model as proposed by Raudkivi and Witte (1990) predicts that smaller bed forms run into larger bed forms. This theory has its basis in the assumption that smaller bed forms migrate faster than larger bed forms. Therefore the larger bed forms resulting from coalescence migrate even slower. The question arises, how do new bed forms develop, because as seen from Figure 5, the number of bed forms does not change dramatically once a stable environment is established for a flow.

The speculation arises that new bed forms develop once an original large bed form gets unstable for the existing flow conditions. What then are the characteristics for bed forms to become unstable?

One parameter responsible for the breaking up of bed forms and therefore creation of new bed forms is assumed to be the rate of sediment transport. As introduced earlier, sediment transport can be defined as the product of wave propagation speed and wave height. Some inconsistencies with this assumption will be analyzed herein, the next section focusing on individual developing bed forms in terms of the two main characteristics that sediment-transport rate is dependent on: bed-form height and bed-form speed.

4.3 Bed-form determination regarding speeds and heights

In order to make comments about bed-form propagation speed and sediment-transport rate, criteria to define individual bed forms are needed. A common approach is to determine local maxima and minima of the recorded time series of bed forms. Once this is done, the calculation of the bed-form propagation speed is the movement of the crest position of an individual sandwave over the recorded time interval. This approach neglects the aspect of changing bedform shape, as displayed in Figure 6. Changes of bed-form shape can be especially observed during the initial stages of bed-form development.

As Figure 7 shows, as a sandwave migrates, the shape of the sandwave changes and therefore speeds determined by crest movement alone, can distort the assessment of true sandwave speeds.

Development of bed-form height over the whole duration of run R/D3 (determined using the approach...
Individual Sandwave Development (Run R/D3) over 10 min

Distance [m]

Elevation

Figure 6. Change of bed-form shape during the development of subaqueous sandwaves (run R/D3 – individual sandwave).

Figure 7. Propagation of an individual sandwave over a period of 10 min (run R/D3).

Figure 8. Development of bed-form height for run R/D3.

According to the writers’ knowledge most studies concentrate on location of crests/troughs through location of local maxima/minima (as indicated above), or use change of lee-slope steepness values to locate the transition from the crest to the lee slope. In terms of determining bed-form heights, both methods give problems in analysis of the present data. Therefore a selected length of bed forms in the developing phase of Run R/D3 was studied in greater detail, mostly via manual considerations. The main aspects studied of locating local maxima/minima) can be seen in Figure 8.

Run R/D3 - Max. and Avg. Bed-Form Heights

Max. Heights
Avg. Heights
10 per. Mov. Avg. Max. Heights
10 per. Mov. Avg. Avg. Heights

Figure 9. Bed-profile plot highlighting the propagation of bed forms (run R/D3).

Figure 10. Bed-form coalescence and generation highlighted from Figure 9.

were determination of bedform shape, and based on that information, calculation of bed-form heights and propagation speeds and sediment-transport rate.

4.4 Bed-form coalescing, generation and life expectancy

Bed-form propagation speed is not only dependent on bed-form shape, but also the environment of the sandwaves interactions with surrounding bed forms influencing bed-form speeds. As a bed develops for a particular flow, new sandwaves can form and old sandwaves will die. This behaviour of sandwaves emerging and dying is directly related to the sediment-transport rate for the flow. For Run R/D3, Figures 9 and 10 show the initial phase of bed development for a 2 m long section of the flume. Figure 10 highlights the emerging and dying sandwaves over the period of bed development.

In Figure 10, newly generated bed forms typically arise after the merging of existing bed forms,
consistent with the throughpassing mechanism highlighted by Coleman and Melville (1994) and Raudkivi and Witte (1990).

The life expectancy of an individual sandwave during bed development has received little attention to date. Figure 11 gives an overview for Run R/D3 of the distribution of sandwaves, over the 10 min period studied, with each sandwave being evaluated according its origin. Figure 11 shows that after 10 min, only 20% of the overall sandwaves were original sandwaves, these having not been consumed in sandwave coalescence.

A relation for the life expectancy of individual sandwaves can possibly be determined as a function of flow, slope, sediment size and water depth. In order to determine such a relation, further analyses of different flow environments and different sediment sizes must be carried out.

4.5 Bed-form speed versus height and sediment transport

Figures 12 and 13 show sediment-transport-rate-related data observed in experimental run R/D3. Because flow and sediment size did not change for this run, the dependency of sandwave propagation speed on sandwave height can be assessed for this run. Once further experimental runs are carried out and analyzed, a comparison with already existing formulas for bed-form speed and sediment transport can be undertaken.

Sandforms propagate downstream by sediment being transported from their stoss sides and deposited on their lee sides (Fig. 13). Based on laboratory data, Coleman and Melville (1994) present a preliminary expression for bed-form speed as a function of flow, sediment and bed-form parameters, that indicates bed-form speed to decrease with increasing bed-form height. Based principally on numerical simulations of bed forms, Nino et al. (2002) similarly conclude that bed-form speed is approximately inversely proportional to bed-form height. Prediction of bed-form speed as a function of flow, sediment and bed-form parameters needs further work however.

Figure 12 shows propagation speeds of individual sandwaves versus sandwave height for Run R/D3. As predicted in the literature, sandwave propagation speed generally decreases with increasing sandwave height, although this result is certainly not clear in the data of Figure 12. Any decrease in speed with increasing height is furthermore small in comparison with other available data (e.g. Baas (1993) and Coleman and Melville (1994)). From Figure 12 it would not be expected that the relations between speed and height in the literature would be true for the present results.

Clearly, the relations predicting bed-form speed as a function of bed-form and flow parameters require further work. In this regard, the concept that bed-form migration speed decreases with increasing bed-form height is central to the bed-form unification model of Raudkivi and Witte (1990). This model, based on the motions and interactions of individual bed features and building on the earlier work of Führböter (1983), provides descriptions that are consistent with physical observations of the evolution from 'plane-bed' conditions to equilibrium of subcritical-flow sediment waves (Coleman and Melville, 1994). Predictions of
this model will be improved, however, with improved modeling of bedform speed as a function of flow, sediment and bed-form parameters.

Figure 13 shows why solely considering speed as a function of sandwave height can provide ambiguous results. Displayed are four sandwaves, namely two pairs of waves that were recorded 30 sec apart. The time gap between the two pairs is 4 min. One can clearly see changes in shape for the four individual bed forms. If sediment transport is taken to be dependent on the average height of two successive sandwaves and the propagation speed measured crest to crest, one comes to the result that the sandwave sediment transport of pair 1 (Fig. 13) is of higher intensity than that for pair 2. In contrast, visual inspection indicates that pair 2 transported in 30 sec more sediment load than pair 1. In this regard, the bed-form shape of pair 2 shows an obvious change in the lee-face steepness, which is not accounted for in calculation of the sediment-transport rate as a function of bed-form speed and height. It is therefore proposed that more attention should be given to the change of shape for successive sandforms. These changes should be incorporated in the calculation of sediment-transport rate. In order to do so, more analyses are necessary to show the dependence of sediment transport on bed-form shape. This research is continuing.

5 CONCLUSIONS

For beds developing to equilibrium, relations central to linkages between bedform propagation, sediment-transport rate and predictions of bed development (e.g. Raudkivi and Witte, 1990) have been investigated herein: principally, the product of bedform speed and bed-form height as bed-forms develop, and the relation of this product to sediment-transport rate; bed-form speed as a function of flow, sediment and bed-form parameters; and the degree to which bed-form geometry can be taken to be similar (including whether steepness can be taken to be constant) as bed forms develop. All these considerations have been analyzed for one main flow, seen as a first major step in a 3 year project. The data and insights of the presented paper will provide the basis of further research in this area.

The next step will be in terms of the last of the above mentioned considerations. In this regard, power-law relations for the growth of sediment-wave lengths and heights with time for steady and changing flows (Coleman and Zhang, 2003) currently indicate that bed-form steepness is essentially invariant during bedform development, although this inference requires confirmation from focused experimental measurements of developing bed forms. Further insight in the still-debated topic of distinctions between ripples and dunes is also expected.

The present experiments and data analysis will be extended to other open-channel flows. In addition to using the present 440 mm-wide glass-sided laboratory flume, there will be data accessible from 135 mm open-channel flows, and rectangular closed conduit flows, with bed development from plane bed to equilibrium configuration measured for each experimental series for a range of homogenous sediments and ranges of flows.

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