Proceedings of the 7th International Conference on HydroScience and Engineering

Philadelphia, USA September 10-13, 2006 (ICHE 2006)

ISBN: 0977447405

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STATISTICAL INTERPRETATION OF GEOMETRIC DIFFERENCES IN RIPPLE AND DUNE SHAPES

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ABSTRACT

A comprehensive data set of three-dimensional sand waves developing from a flat bed to equilibrium stage was obtained during experimental investigations (SWAT.nz - Sand Waves and Turbulence New Zealand) in a 440-mm-wide flume at The University of Auckland. The present paper addresses initial research on geometric shape differences between the two common bed forms, ripples and dunes, with the help of high-order distribution moments.

Statistical interpretation of continuous spatial series is introduced as a tool to decide whether a bed consists of ripples or dunes. Importantly, the question arises: What happens when a plane bed of fine sediment (d_{50}=0.24-mm) is exposed to a flow where initially ripples and later dunes develop? Experiments over fixed bed forms show differences of the flow field over different topographic shapes. In order to take a step forward and analyze in more detail the feedback mechanism between flow structures and mobile-bed sediment structures, one needs an objective tool to verify the configuration of the bed forms interacting with the flow structures, especially as bed forms can undergo important transformations throughout their development. In the following we discuss whether ripple-dune transition for a constant flow is evidenced by distribution moments, specifically skewness and kurtosis values.

An extensive background of the physical differences between ripples and dunes, in terms of their geometry as well as their interaction with the flow field, is provided. The statistical analyses are introduced and results are discussed. Special attention is given to the physical background of the ripple-dune transition and its interpretation with high-order statistics.

1. INTRODUCTION

Commonly, researchers in laboratories use conventional methods based on the median sediment grain size and predominant flow velocities and flow depths in order to determine whether a ripple bed or a dune bed will develop over a sand bed for certain flow conditions.

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As ripples and dunes form with different flow conditions for a given sediment (e.g. Ashley, 1990; Baas, 1999; Leeder, 1983), one knows what bed form to expect for equilibrium conditions. But what happens during the development of fine sand when exposed to a flow, where initially ripples form but later dunes develop? How can we determine where the transition between ripple and dune states will occur?

This ability of underwater sand beds to change their status is still not satisfactorily explained, be it for unsteady flow conditions or for steady flows (Schindler and Robert, 2005).

Studies have been undertaken for fixed bed forms, in order to gain knowledge about the differences in the flow field over ripple (Wiberg and Nelson, 1992, Bennett and Best, 1996) and dune (Nelson and Smith, 1989, Nelson et al., 1993, McLean et al., 1994, Bennett and Best, 1995) topographies. Although valuable new insights are gained with fixed bed studies (e.g. turbulence statistics; mean velocity distributions; local origins of turbulence; dynamic effects causing pressure fluctuations; Reynolds stresses), neglecting the mobility of the transported sediments withholds fundamental information and restricts our understanding of how bed forms develop. The interaction between the flow field and the movable sediment is central to how bed forms exist and migrate. This interaction can not be studied with fixed bed forms. The next advances in understanding the behaviors of sand waves will arise from studies of the flow field characteristics over mobile beds. In order to do so, one needs an objective criteria of how to distinguish between ripples and dunes, as a sand bed can experience both modes for certain median sediment grain sizes and flow conditions.

The present paper addresses geometric shape differences between ripples and dunes with the help of high-order distribution moments of bed elevations. Specifically, the focus herein is on interpretation of bed-elevation skewness and kurtosis. Symmetry, or the lack of symmetry, for a data set is indicated by the distribution skewness. A data set with a high kurtosis value can be interpreted as being a distribution of a unique peak near the mean that drops rather rapidly and then tails off slowly away from the mean when compared to the normal distribution. Distribution plateaus near the mean are typically represented by low kurtosis values.

We present measurements of bed form statistics from our laboratory data set and use analyses of skewness and kurtosis as a way to show differences in ripple and dune geometry. The aims of this paper are: (i) to provide a detailed overview of why it is important to have an objective way to classify bed forms, and (ii) to introduce particular tools of time-series analysis of bed elevation, namely skewness and kurtosis to classify bed forms.

2. THEORETICAL BACKGROUND

2.1 Geometric differences between ripples and dunes

On a first look there are only superficial differences between ripples and dunes. These small differences, however, have long been argued as being founded on significant morphological differences (Simons et al., 1965). As one common feature, sand waves in laboratory experiments are aligned transverse to the mean flow along the flume. Bed forms which display an astonishing regularity when seen as a whole field comprise features which can range from a few centimeters in length to hundreds of meters in length. The abovementioned regularity is typically described as height, length and steepness parameters in statistical terms (Ashley, 1990; Raudkivi, 1999). At the same time, although a field of bed forms can show a certain regularity, individual bed forms show an irregularity in terms of shape and size. Figure 1 shows a 3-D rippled bed on the left and a 2-D dune bed on the right, demonstrating the relative irregularity for ripples compared to dunes as observed in the width-restrained environment of a 0.44-m-wide flume.

Ripples do not scale with flow depth, but are dependent on the median grain size d_{50} and the grain Reynolds number $Re_g=u_*d_{50}/\nu$, (where u_* is the shear velocity and ν is the kinematic viscosity). Ripples do not form with sediment size >0.6-mm, are no higher than 0.03-m and no longer than 0.6-m (Bennett and Best, 1996). Many studies in the past focused on ripple development (Baas, 1994; Baas, 1999; Raudkivi, 1997).

In contrast, dunes do influence the flow field over the whole depth of a river environment. In off-shore environments, dunes have been found in hundreds of meters depth, suggesting that a local boundary layer is responsible for the development of dunes. In the river environment this is the flow depth. Dunes form in sediment >0.15-mm median grain size diameter, and dune length is around *6D*, with *D* being the water depth.

When it comes to the ripple-dune transition, only a few researchers have investigated the physical processes of this transformation, amongst them Bennett and Best (1996); Lopez et al. (2000) and Robert and Uhlman (2001). Leeder (1983) was one of the earliest to argue that bigger size ripples, he called them 'rogue' ripples, cause deeper scour holes on their lee-side and thus increase the sediment transport and in order to sustain the increase in sediment flux they increase their height and change to dunes. The complex ripple-dune transformation provides a notable platform for much disagreement in the sand-wave community.

Figure 1 Ripple (left) and dune (right) beds in as seen in the 0.44-m wide flume at the University of Auckland.

2.2 Flow field differences between ripples and dunes

Bed forms impose form drag, which increases the flow resistance in the stream. They are associated with turbulence generation near the bed. The necessity of transporting sediment imposes changes on the stream elements. The interaction between flow field, bed morphology and sediment transport keeps the stream in balance (Bagnold, 1956).

With the help of experiments over fixed bed forms (ripple: Wiberg and Nelson (1992) and Bennett and Best (1996); dune: Nelson and Smith (1989), Nelson et al. (1993), McLean et al. (1994) and Bennett & Best (1995)) one tries to identify the flow field differences based on topographic differences of the bed forms. Advances in the understanding of flow separation, internal boundary layer development and associated turbulence structure are notable (Robert & Uhlman, 2001).

Flow fields over ripples are more uniform, and they experience a relatively low degree turbulent activity. Turbulent ejection events dissipate rather rapidly. Therefore the shear layer is restricted to near bed regions. Dune topography is larger than that for ripples. The surrounding flow field is influenced by the dunes over the whole depth for river environments and experiences a periodical acceleration and deceleration. Generally speaking, the velocity gradient over dunes is greater than over ripples, which results in stronger shear layer activity. Therefore, a larger section of the water column is influenced by the dunes, with vortex shedding dominating the lower part of the flow depth. Often visible boils at the water surface have their origin in ejection events at the sand surface. A critical change in the flow structure is responsible for the transition from ripples to dunes.

Generally speaking, an increase in erosion at the reattachment point results in an increase in crest height, as here the sediment will be mainly deposited over the upstream bed form slope. Therefore, a larger separation zone exists and growth of bed form length is stronger (Schindler and Robert, 2005).

The recent study of Fernandez et al. (2006) describes the influence of bed-form superposition on flow fields. Bed-form amalgamation, which results in bed-form superpositions during the ripple-dune transition, results in the production of higher Reynolds stresses near to and downstream of the flow attachment. Furthermore, the above-mentioned study also supports the studies of Schindler and Robert (2004) and Schindler and Robert (2005) which report increases in suspended-sediment concentrations across the ripple-dune transition, and therefore show the necessity of studying the flow fields over mobile beds as a next step to future achievements in understanding the development of submerged sediment waves.

3. EXPERIMENTAL SETUP

The main objective of the experiments was to observe changes in bed-form development (starting from a flat bed) utilizing two different sediment sizes and two different water depths for a number of steady mean flow velocities. The data utilized for this paper are part of the Sand Waves and Turbulence research program undertaken in New Zealand (SWAT.nz). The experimental setup and measurement procedure are introduced in a general manner in Friedrich et al. (2005). Sixteen experiments, each with a different composition of sediment size, flow depth and mean flow velocity were carried out in a 12m-long, 0.38m-deep and 0.44m-wide, glass-sided, open-channel flume. Experimental parameters are given in Table 1. Each experiment was repeated, therefore altogether 32 data sets of bed-form development were obtained. In the operation of the flume, both water and sediment were continuously re-circulated.

Experiments were carried out with two different uniform sands and two water depths, D=0.15-m and 0.22-m. The sands in use were a fine sand with median size d_{50} = 0.24-mm and a coarse sand with d_{50} = 0.85-mm. Development was recorded for a minimum of 200-min (high Froude numbers) and up to 360-min (low Froude numbers) for each experiment. Froude number F for the 16 experiments ranged from 0.26 to 0.6.

The sand in the flume was first flattened and then exposed to the mean velocity. All mobile bed runs reached equilibrium stages of bed-form development. Acoustic sensors were utilized (Friedrich et al., 2005) to measure the 3-D development of bed forms. Measurements of bed elevation, using a grid of 17.5-cm x 6.25-m, were made every minute along the centerline of the 0.44-m wide and 12-m long flume. For analysis purposes, the recorded area can be divided into eight longitudinal profiles with a transverse resolution of 25-mm. For this paper each of these 8 longitudinal profiles are analyzed separately and the results are averaged. Figure 3 shows the development of the centerline longitudinal profiles for runs ndf23b and ndc325b.

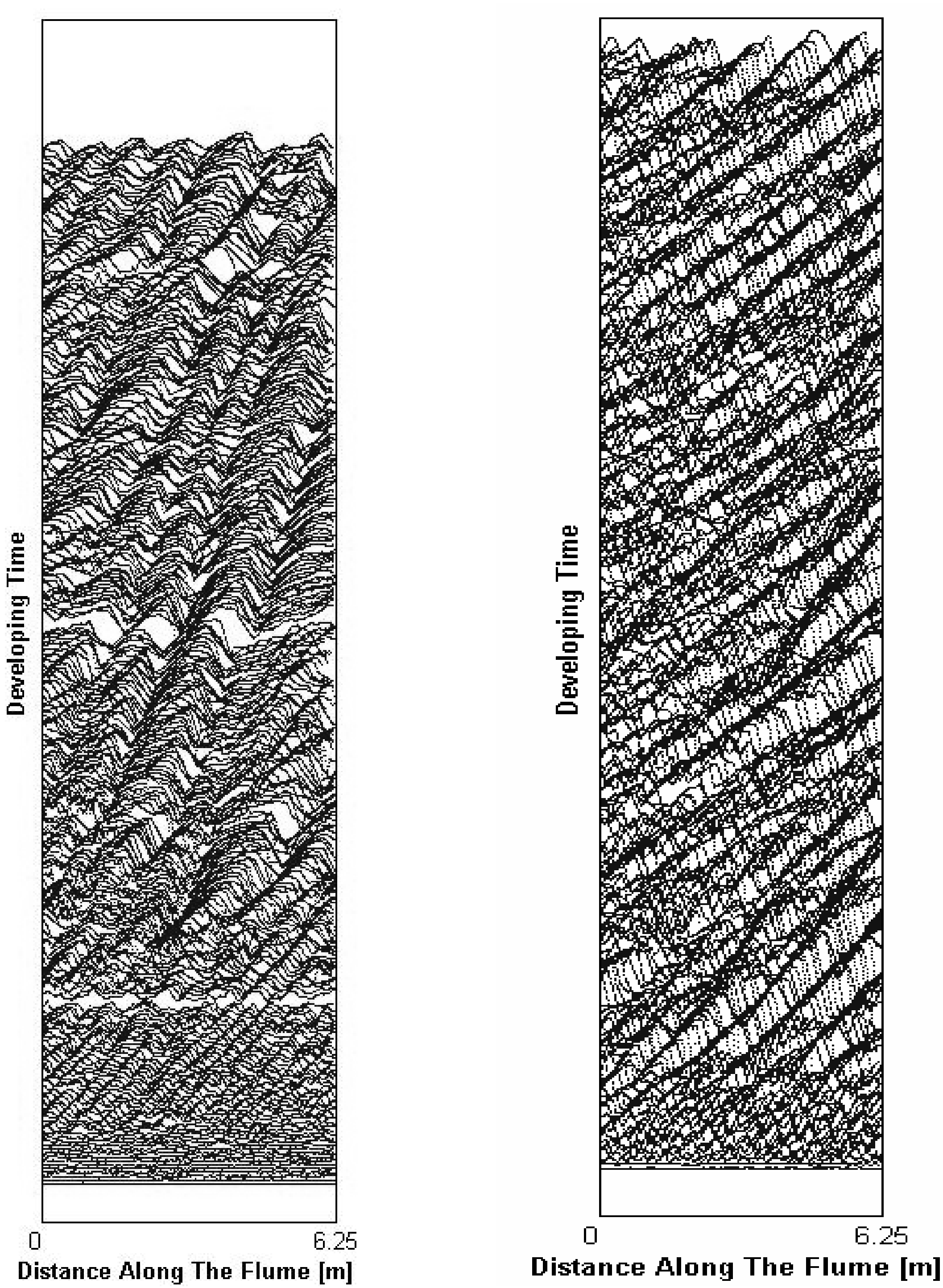

Figure 3 Recording of development of sand beds starting from flat bed for fine and coarse sand: left ndf23b – centerline profile (fine sand); right ndc325b – centerline profile (coarse sand). Profiles are 1-min apart with the gaps being due to re-adjusting the mobile carriage carrying the measuring equipment.

Table 1 Overview of experimental parameters.

Run Name	d_{50} [mm]	D [m]	T [°C]	S_e [-]	U_{avg} [m/s]	Fr [-]	Re ($x10^3$)
nsf10	0.24	0.15	20/22	0.1	0.35	0.289	31
nsf125	0.24	0.15	20/22	0.1	0.43	0.354	38
nsf14	0.24	0.15	20/22	0.1	0.46	0.379	41
nsf18	0.24	0.15	20	0.1	0.61	0.503	54
nsc175	0.85	0.15	18	0.17	0.57	0.470	51
nsc20	0.85	0.15	18	0.23	0.61	0.503	54
nsc22	0.85	0.15	18	0.27	0.67	0.552	60
nsc24	0.85	0.15	18	0.3	0.72	0.594	64
ndf14	0.24	0.22	22	0.1	0.38	0.259	42
ndf17	0.24	0.22	22	0.1	0.47	0.320	52
ndf20	0.24	0.22	22	0.1	0.56	0.381	62
ndf23	0.24	0.22	22	0.1	0.65	0.442	72
ndc225	0.85	0.22	19	0.1	0.59	0.402	65
ndc275	0.85	0.22	19	0.1	0.7	0.476	77
ndc305	0.85	0.22	19	0.1	0.78	0.531	86
ndc325	0.85	0.22	19	0.1	0.83	0.565	91

Note: Kinematic viscosity ν=0.000001-m^2/s; Specific gravity s=2.65; Critical shear velocity u_{*c}(d_{50}=0.24mm)=0.0132m/s, u_{*c}(d_{50}=0.85-mm)=0.0215m/s

d_{50} Median grain size, D Flow Depth, T Water Temperature, S_e Flume Slope, U_{avg} Average Flow Velocity, Fr Froude Number, Re Reynolds Number, m Hydraulic Radius (A/2D+B), A Cross-sectional area of the flow, B Flume Width, Re=m*U_{avg}/ν

4. STATISTICAL INTERPRETATION AND DATA ANALYSIS

Commonly, sand-wave analysis has been undertaken in the past using a discrete approach, which utilizes a system of geometric (length, height, steepness, etc.) and kinematic (velocity of propagation) parameters. Here we propose to treat a recorded 3-D sand-bed elevation field as a random field rather than a series of discrete sand waves. Nordin and Algert (1966), Hino (1968), Jain and Kennedy (1974) treated bed-form profiles as a continuous time series and applied spectral analysis. Most recently Nikora et al. (1997) treated sand-bed elevation fields as random fields rather than discrete sand waves, using longitudinal and transverse spectra, correlation and structure functions to describe statistical sand wave dynamics.

In this paper, we evaluate the use of basic higher-order distribution moments of bed elevation in order to classify ripple and dune topographies. The advantage of using distribution moments, such as the 3rd-order moment skewness and the 4th-order moment kurtosis is that results are independent of the mean of a series of bed-form profiles, as well as the resolution at which the bed profiles have been recorded – (see Section 5).

Skewness and kurtosis analysis has been widely used in other areas, such as sea level variability of oceans (Thompson and Demirov, 2006). It is shown with skewness analysis that ocean features such as the Gulf Stream, the Kuroshio Extension, the Brazil-Malvinas Confluence, and the Agulhas Retroflection can be seen. Thompson and Demirov (2006) also show that sea-level skewness can be used to identify the mean path of unstable ocean jets and also regions dominated by eddies with a preferred sense of rotation. The question arises if skewness/ kurtosis analysis can also be used in the field of submerged sediment waves to distinguish between features such as ripples and dunes, which will be important for future studies as shown under Section 2.

The common statistical properties for time-series are the first- and second-order distribution moments. The first-order moment represents the mean, which for sand-bed profiles recorded in laboratory studies along a limited section of a flume can be used to check the sediment balance over time over that section. The mean $\bar{x}$ is obtained by summing all members of a spatial series x_i, with i=1 to N, N being the number of samples in one series, and dividing by N.

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{1}$$

The second-order moment is the standard deviation σ, often used to show the growth of sand waves during development.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{2}$$

The 3rd- and 4th-order moments (see Figure 4 for their interpretation) are neglected in most of the studies about sand waves. The 3rd–order distribution moment skewness is a measure of the symmetry/asymmetry of a spatial series relative to the normal distribution. A skewness value of zero stands for a symmetric distribution around the sample mean. A negative skewness value means that the data are spread out more to the left of the mean than to the right and a positive skewness value means that the data are spread out more to the right. The skewness sk is calculated as the ratio of μ_3, the third moment about the mean to the cube of the standard deviation, namely

$$sk = \frac{\mu_3}{\sigma^3} \tag{3}$$

Kurtosis, the 4th-order moment is a measure of the peakedness or flatness of a spatial series distribution. Higher kurtosis values mean more of the variance in a spatial series is due to infrequent extreme deviations, as opposed to frequent modestly-sized deviations for lower kurtosis values. As the kurtosis value of a normal distribution is 3, a correction is commonly made to obtain a kurtosis value of zero for a normal distribution. Therefore, a kurtosis value of zero stands for a symmetric distribution around the sample mean. A negative kurtosis value means that the data are flat (platycurtic) and a positive kurtosis value means that the data exhibit more extreme fluctuations. The kurtosis ku is calculated

$$ku = \frac{\mu_4}{\sigma^4} - 3 \tag{4}$$

where μ_4 is the fourth moment about the mean.

For our analysis, the eight longitudinal profiles recorded for each sweep along the flume were initially considered individually. Filtering methods were applied to remove faulty signals and to take into account the detection of suspended particles. Faulty signals were eliminated with a cut-off criterion which utilizes the maximum crest and minimum trough elevations throughout the development as a threshold. The thresholds were set manually after inspecting the bed-form development for each individual experiment. Suspended particles were eliminated by calculating the height difference for neighboring sampling points over a certain number of points, manually setting a tolerance threshold for the maximum height difference allowed, based again on data observations, and visually verifying the results. Afterwards, interpolation procedures were used to fill the gaps in the profiles. The sand-bed elevation surfaces were then adjusted to incorporate the flume slope. For each of the eight longitudinal profiles of every sweep, skewness and kurtosis values were calculated and a final value was obtained by averaging over the eight individual values.

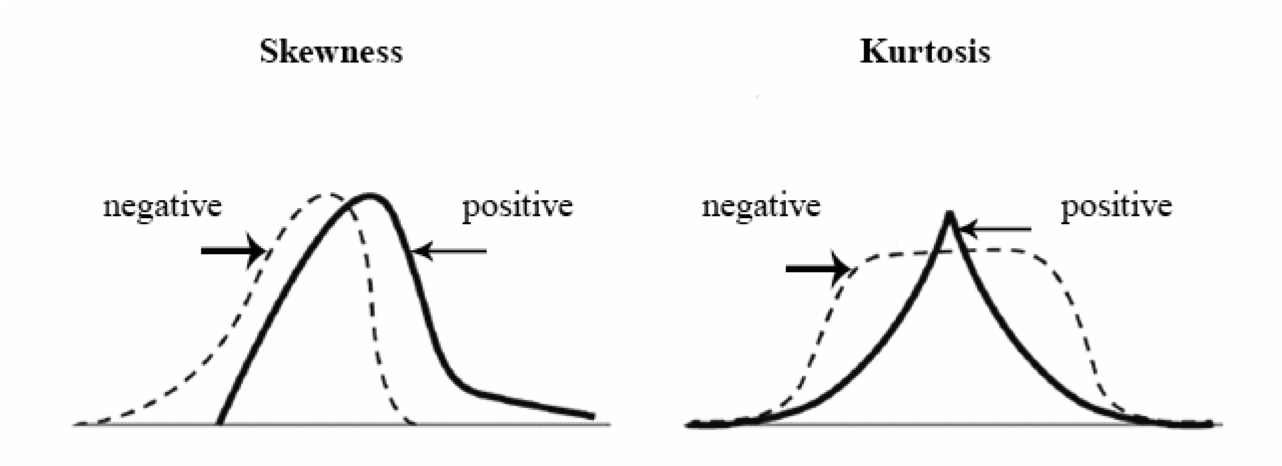

Figure 4 Schematic overview of skewness and kurtosis characteristics for topographic shapes.

5. RESULTS

Based on the analyses as described above, skewness and kurtosis values were determined for each sweep, namely every minute of a run. As a preliminary study, three of the experimental runs were analyzed. These were: One run with fine sand where ripples developed, one run of coarse sand showing dune development, and one run using fine sand that according to common prediction diagrams should develop a dune bed eventually, after potentially going through a ripple stage. Values for skewness and kurtosis over the whole development from flat bed to equilibrium for each run were put into a scatter plot (Figure 5).

As shown in Figure 5, for a ripple geometry (ndf17a – fine sand ripple), skewness and kurtosis values plot in the upper-right quadrant. Dune geometry (ndc325b – coarse sand dune) is generally defined by a negative skewness. For the very beginning of fine-sand (d_{50}=0.24-mm) bed-form development for a fast flow (ndf23b – fine sand dune), skewness and kurtosis values were similar to those for ripples in fine sand exposed to a slow flow. Later in this experiment, skewness and kurtosis values are equivalent to those for a dune bed. The results of Figure 5 suggest that the moment when the transition from ripple to dune features takes place (for growth from a plane bed subject to a given flow) can be assessed and investigated based on high-order statistics.

Restrictions to the validity of the above shown plot must be discussed, as closer examination of the recorded ripple beds revealed a high amount of suspended particles which had been recorded and resulted in a noisy bed-profile. During the filtering and interpolation process, the limit of the algorithms had been reached and often linear approximations were applied to the eventual bed-form shape. In order to confirm that the results in Figure 5 are based on ripple bed-forms with as little error in the data as possible, sample data of previous ripple development studies undertaken by the authors are used for the remaining discussion about differences in high-order distribution moments for ripple and dune shapes.

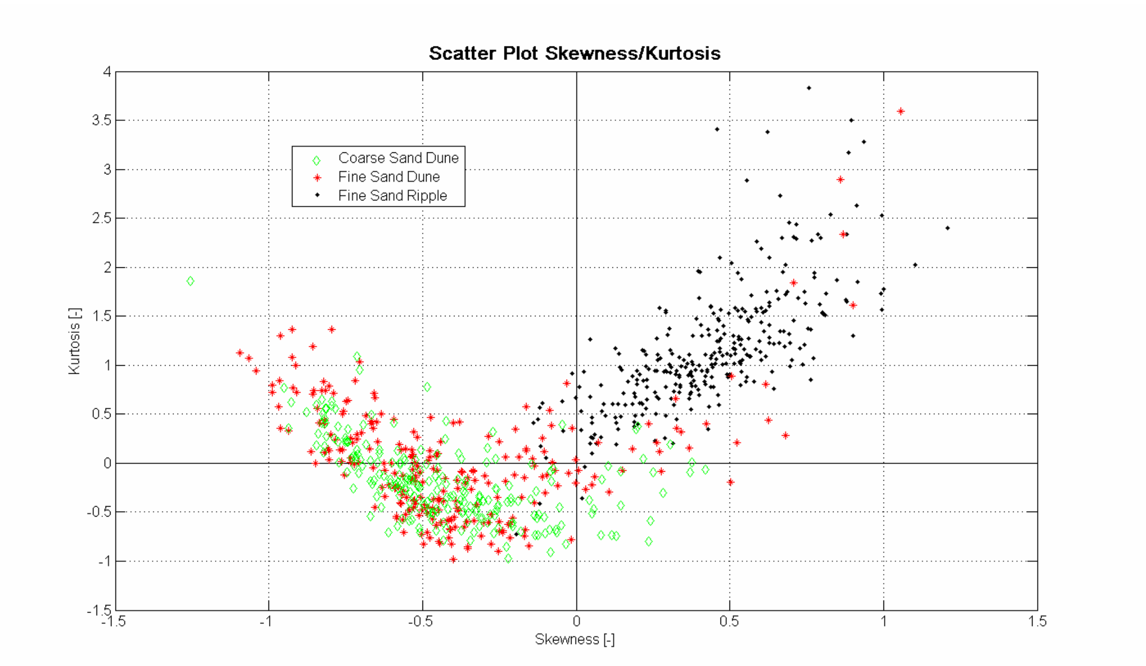

Figure 5 Skewness vs kurtosis for bed forms developing from flat bed conditions.

After further testing of the data, it was concluded that the higher kurtosis values for the ndf17a (fine sand ripple) run are caused by the noisy data. Kurtosis values for dune and ripple shapes should fluctuate around zero, with dune shapes exhibiting slightly lower values than ripples (see Figure 7). The testing also showed that the skewness value principally indicates differences of ripple and dune topographies.

It was therefore decided to concentrate on the skewness interpretation. In order to do so, and to discuss possible topographic influences on skewness values for time-series evaluation, the following sample profiles (Table 2) have been put together (see Figure 6) and analyzed.

Table 2 Overview of sample profiles P1 to P24.

Name	**Description**	**Type (visual observation backed up with Figure 8)**
P1	profile of ndc325b – 3.5hrs into development – centerline	Dune
P2	profile of ndf23b – 3.5hrs into development – centerline	Dune
P3	triangle profile, as often used for fixed bed form experiments	Triangle
P4	triangle profile with a concave upwards stoss-side face	Ripple
P5	triangle profile with a convex upwards stoss-side face	Dune
P6	profile with regular periodicity	Dune
P7	same as P3, shorter stoss side	Triangle
P8	same as P8, but with cosine stoss side	Triangle
P9	same as P5, shorter stoss side	Dune
P10	same as P4, shorter stoss side	Ripple
P11	profile of ndf23b – 20min into development – centerline	Ripple

Name	Description	Type (visual observation backed up with Figure 8)
P12	profile from previous experiments by the authors, using the same sand, flume and flow velocities as the fine sand runs	Ripple
P13	profile with regular periodicity	Ripple
P14	same as P7, smaller amplitude	Triangle
P15	same as P8, smaller amplitude	Triangle
P16	same as P9, smaller amplitude	Dune
P17	same as P10, smaller amplitude	Ripple
P18	same as P14, smaller amplitude	Triangle
P19	same as P15, smaller amplitude	Triangle
P20	same as P16, smaller amplitude	Dune
P21	same as P17, smaller amplitude	Ripple
P22	P5 and P9 combined	Dune
P23	P4 and P10 combined	Ripple
P24	P3 and P7 combined	Triangle

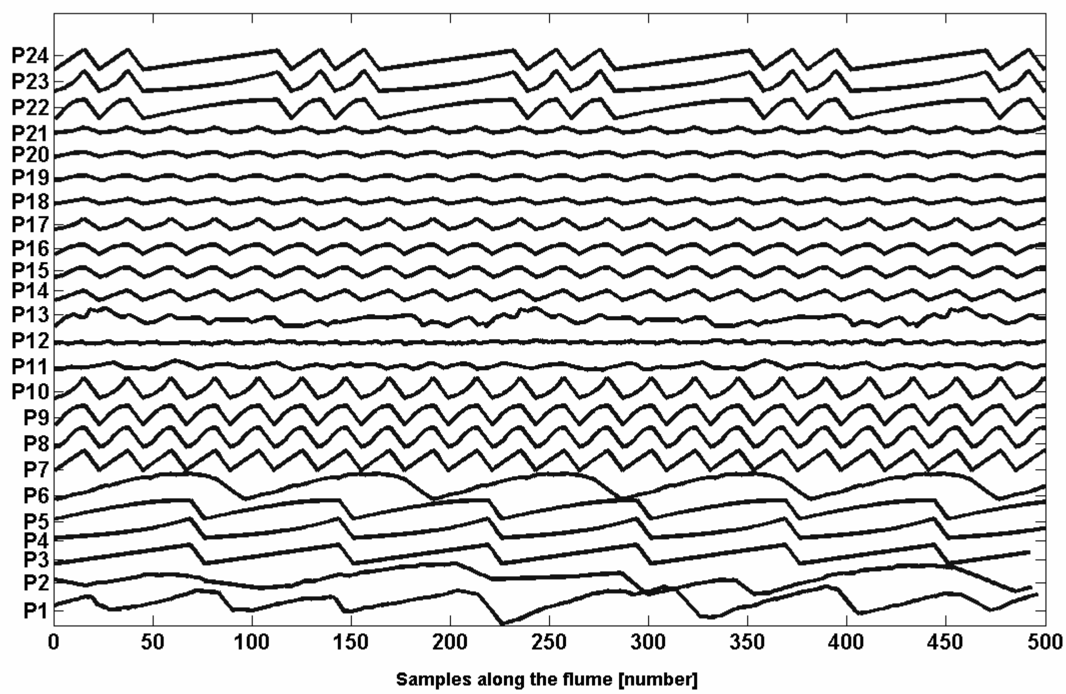

Figure 6 Topography of shapes P1 to P24.

For this preliminary study, we paid special attention to the following aspects which could influence the skewness values: *length of recorded profile; regularity of the periodicity of bed forms; stoss-side shape of the bed forms;* and *sampling resolution of the recorded bed profile.*

Length of recorded profile: Our experimental recording length was 6.25-m (equal to 500 samples with a sampling resolution of 1.25-cm). For the deep flow of *D*=0.22-m, the maximum length of a dune was expected to be 1.3-m (*l=6D*). Profiles P1, P2 and P3 consist of between 5 and 7 dune shapes, over 6.25-m. As often the first and last bed-form shape of a spatial series is not recorded completely, the influence of that irregularity when determining skewness values was also tested. Figure 7 shows the change of skewness and kurtosis values for dune/ripple profiles of the sample P-series, indicating how many samples have to be taken into account to obtain realistic skewness values for a time-series recorded under our flume conditions. One can see that when more than 100 samples are taken into account, the skewness/kurtosis values start to fluctuate around the mean, with fluctuation reducing if more samples are included. Therefore we can say that our sample range is large enough to obtain reasonable values for skewness and kurtosis, and over a length of 500 samples the influence of capturing only parts of individual bed forms at the beginning and end of a recording cycle is negligible.

Regularity of the periodicity of bed forms: Experiments in a 0.44-m wide flume result in either 3-D ripples or 2-D dunes, as the lateral boundaries and small width of the flume restrict 3-D dune development. As fixed bed-form experiments are often undertaken in flumes of similar width over fixed beds, and typically use bed-form shapes of regular periodicity, the fact that 3-D ripple beds have a much higher degree of uneven topographical intervals should be given special attention when analyzing high-order distribution moments. From Figure 7, one can see that for irregular longitudinal shapes, the fluctuation around the mean for skewness/kurtosis is less pronounced than for regular periodic shapes. Nevertheless, ripple samples typically exhibit higher skewness values than dune samples.

Stoss-side shape of bed forms: Sediment is transported as bed-load over the stoss side of the dunes. Often superposition of bed forms occurs, which imprints a covex upwards curvature on the stoss-side dune profile. For ripples, the stoss side can be often as long as the lee side, housing turbulent eddies. A higher degree of upstream steepness for ripple shapes, based on the shorter stoss side, as compared to dunes, would result in skewness values close to zero, as for a normal distribution. Additionally, the smaller amount of bed-load transport over the stoss-side of the ripple and the non-existence of superposition can even result in an inward curvature of the stoss-side, which results in positive skewness values for ripple values compared to negative values for dune shapes (see Figure 8).

Sampling resolution of the recorded bed profile: Analyzing the same topographies, but with different sample resolutions, showed that as long as the main features of a sand bed covered with sand waves are recognizable, skewness and kurtosis analysis can be applied and provide satisfactory information to discuss the shape difference.

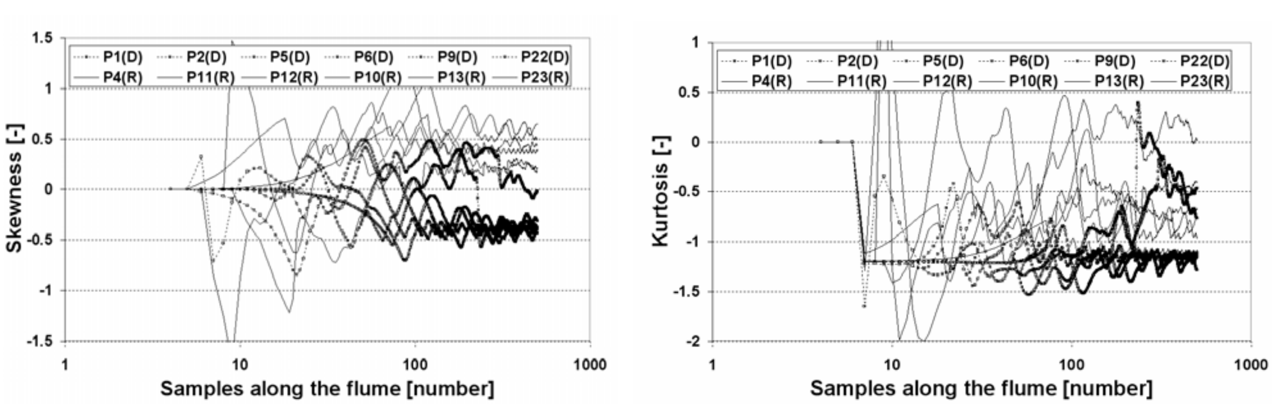

Figure 7 Influence of time-series length on skewness (left) and kurtosis (right) values for dune (dash line with square marker) and ripple (solid line) shapes.

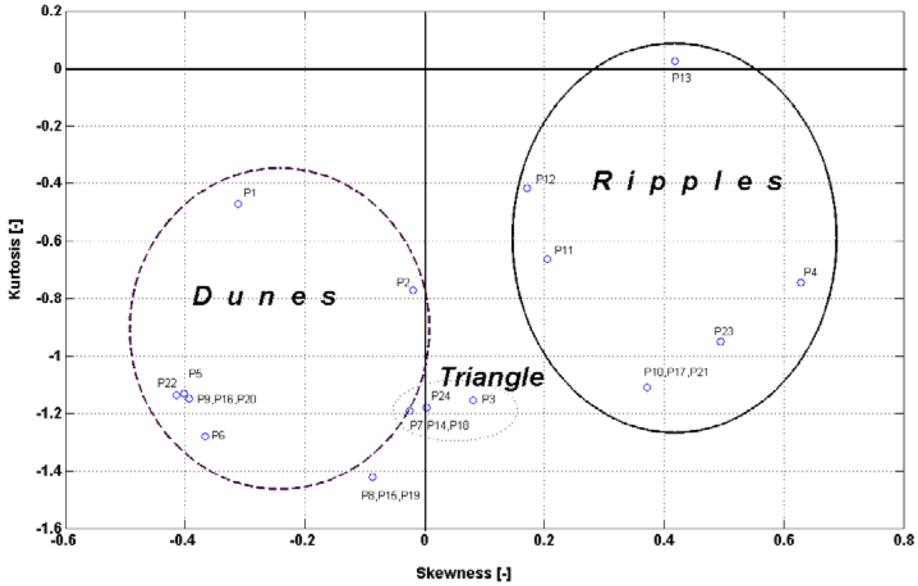

Figure 8 Skewness vs kurtosis for shapes P1 to P24.

6. SUMMARY

In this paper we present an overview showing the geometric differences for ripples and dunes, two of the most important and most researched submerged sediment waves. It is important to have a way to classify whether a sand bed is covered by either ripples or dunes, especially when it comes to future flow field studies over mobile beds. Additionally, the ability to classify recorded sand beds without knowing all the boundary conditions like sediment median grain size, flow velocity and flow depth will be of key significance for real flow environments, outside laboratory conditions.

Research into sand wave statistics has utilized a discrete approach in the past. Here we treat sand-bed elevations as a random field rather than as discrete sand waves. High-order distribution moments are introduced and applied to a limited portion of an experimental data set for preliminary analysis.

It is shown that dunes exhibit a negative skewness based on their long, convex upwards stoss-side slope and relative steep and short lee-side face. The upstream slope is commonly superposed with other sand waves, therefore giving the above-mentioned curvature, which can be described as a humpback.

During the preliminary analysis, it was shown that for the fine sand data of d_{50}=0.24-mm a high amount of suspended particles resulted in less accurate description of the ripple bed profile. Further ripple data sets need to be analyzed to support the hypothesis that high-order distribution moments can be used to classify 3-D ripples and dunes unambiguously.

As a summary, the use of high-order distribution moments for evaluating time-series of recorded sand-bed profiles requires further investigation. Applying theoretical bed-profile shapes to high-order distribution analysis shows considerable differences between dune and 3-D ripple profiles, which helps validate the method of analysis and emphasizes the need for further research in this area.

ACKNOWLEDGEMENTS

The research was partly funded by the Marsden Fund (UOA220) administered by the New Zealand Royal Society. The authors are grateful to Dr D. Goring for useful discussions and to Mr. T.M. Clunie for help with the experiments.

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