FLUME INFLUENCE ON DEVELOPING DUNE BEDS

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ABSTRACT

This paper presents the results of a flume comparison study undertaken at the University of Auckland. Data from a comprehensive set of three-dimensional sand waves developing from a flat bed to equilibrium stage were obtained during experimental investigations (SWAT.nz - Sand Waves and Turbulence New Zealand). Two flumes, 0.44-m-wide and 1.5-m-wide, were utilized for the experiments. Runs were undertaken with different flow depths, median grain sediment sizes, and flow velocities. For this paper two experiments with similar flow conditions and Froude numbers are analyzed in more detail. Side-wall effects and bed-form growth are studied. The study is part of a series of studies looking at the phenomenon of submerged sediment-bed-form behaviour. The analyzes show increase in bed-form height with flume width increase. This is mainly caused by the side-walls of the narrower flume imposing a physical restriction to the lateral spread of both the 3-D turbulent flow field and the dune development. The wider flume allowed the full development of bed-form width across the flume for shallow flow. The increase in bed-form growth observed closer to the side-walls is associated with different erosion and deposition patterns closer to the wall. The bed-form growth pattern is not affected by the side walls over roughly the centre 30% for both flumes, when the centreline longitudinal profile is taken as a reference value.

Keywords: Flume; scaling; growth; dune; side-wall effect.

1 INTRODUCTION

1.1. BACKGROUND

Experiments simulating natural river environments in laboratory flumes have been conducted for over a century. However, our understanding of fluvial processes still remains rudimentary because of the complex conditions in natural environments. Laboratory studies enable us to simulate natural environments in a simplified manner. Natural environments feature geometrically different boundary conditions than those typically found in laboratory flumes. It is difficult to conduct measurements in steady conditions in river environments, where often unsteady flow conditions as well as intermittent sediment supply predominate. Laboratory research allows systematic study of water-sediment interaction under steady flows, which can then be used to gain information for less steady flows, albeit with much shallower flows.

In the area of bed-form development, physical models have been implemented since early in the last century. When comparing bed-form data obtained by laboratory experiments, how to define the geometric shapes of bed forms, and how to define the environment in which bed forms were recorded, are important considerations. The latter is commonly simplified by recording a longitudinal profile in spatial or temporal dimension on the centreline of the flume. Williams (1970) studied the effects of flume width and water depth on sediment transport. He concluded that flume width has no influence on the unit discharge-unit sediment transport relations and the mean velocity transport relations at constant water depth. Crickmore (1970) studied the effect of flume width on bed-form characteristics. He observed an increase in height, length and spectral width with increasing flume width. He suggested that relatively wide channels are required for studies of bed forms in coarse sand. Crickmore (1970) also emphasized the need to give attention to what constitutes a bed-form unit.

For this paper we consider only dunes, and do not include ripples. A common problem when defining dune shapes for discrete bed profiles is the application of a manual or automatic algorithm, providing height, length and steepness information. Depending on subjective definitions, it provides data only on features with certain heights and lengths, thus making it subjective as to what constitutes a dune and neglecting other possibly important information. Treating a sand-bed-elevation field as a random field rather than discrete sand waves for the analysis of bed-form growth provides an objective tool and comparison studies can be performed more easily, as the lack of clear definitions to what constitutes a bed form does not affect the results.

No recent study is known to the authors where the longitudinal development of dunes is compared across the flume. Therefore the authors used experimental data of developing dunes from a flat bed, obtained from two different flumes, a wide and a narrow flume, to study the effect of flume width and side-wall influence on the growth of bed forms. In this paper, two experiments with similar flow conditions and Froude numbers are analyzed in more detail.

2 BED-FORM DEVELOPMENT

Commonly, sand waves are seen as individual bed forms, having certain height, length and steepness parameters. The dimensionless growth rate of dunes from a flat sand bed is dependent on the equilibrium height/length parameter as well as the equilibrium time for the dunes to be fully developed. Commonly, bed-form growth is proposed to be a power law (Nikora and Hicks, 1997)

$$\frac{h}{h_e} = \left(\frac{t}{t_e} \right)^{\gamma} \qquad \text{(Eq.1)}$$

with h being the height of the bed form after time t of development, and h_e the equilibrium height after time t_e of development. A growth exponent γ expresses the exponential growth characteristics of bed forms, displaying rapid growth from a flat bed, with a slower approach to equilibrium conditions. Nikora and Hicks (1997) propose γ to be universal and equal to 0.28. As sand waves are seen as self-similar features, meaning that during development their height parameters increases proportionally to their length parameters, h and h_e can be exchanged for l, being the length of a bed form and l_e, being the equilibrium length after time t_e of development. The power law is not valid for the initial stages of bed-form development, when the initial wave length l_{wi} is dependent on the sediment median grain size (Coleman and Melville, 1996).

Here we propose to treat a recorded 3-D sand-bed elevation field as a random field rather than as discrete sand waves. Nordin and Algert (1966), Hino (1968) and Jain and Kennedy (1974) treated bed-form profiles as a continuous time series and applied spectral analysis. More 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.

Nikora and Hicks (1997) also introduce scaling relationships when sand wave fields are considered as a random field of bottom elevations. The root-mean-square deviation $\sigma_z(\delta x, t)$ over a certain distance δx (ranges from the smallest possible sub distance available for the profile up to the whole length of the profile) along the flume, at a certain time t during development, can be used to express similar scaling relationships to Eq.1. A double scaling form is proposed

$$\frac{\sigma_z(\delta x, t)}{\sigma_{z0}} = \left(\frac{t}{t_e} \right)^{\gamma} f\left[\left(\frac{\delta x}{\delta x_0} \right) \Big/ \left(\frac{t}{t_e} \right)^{\gamma} \right] \qquad \text{(Eq.2)}$$

where $\sigma_{z0}=\sigma_z(\delta x, t)$ when $\delta x \geq \delta x_0$ and $t \geq t_e$. $\delta x_0=\delta x$ when $\sigma_z(\delta x,\ t_e)$ becomes saturated for equilibrium conditions.

By analogy to height and length parameters being inter-exchangeable growth parameters when applying the power law (Eq.1) for discrete sand waves, there must exist a similarity relationship between $\sigma_z(\delta x)$ and δx for random fields. For self-similar features, which longitudinal spatial sand wave profiles are considered to be, $\sigma_z(\delta x) \propto \delta x$ (see Figure 1). Therefore δx is a characteristic scaling feature of the developing dune bed, similar to the wave length feature of discrete sand wave analysis. δx will grow similar to a discrete wave length during the development of the dune bed and will reach an equilibrium stage once saturation is reached.

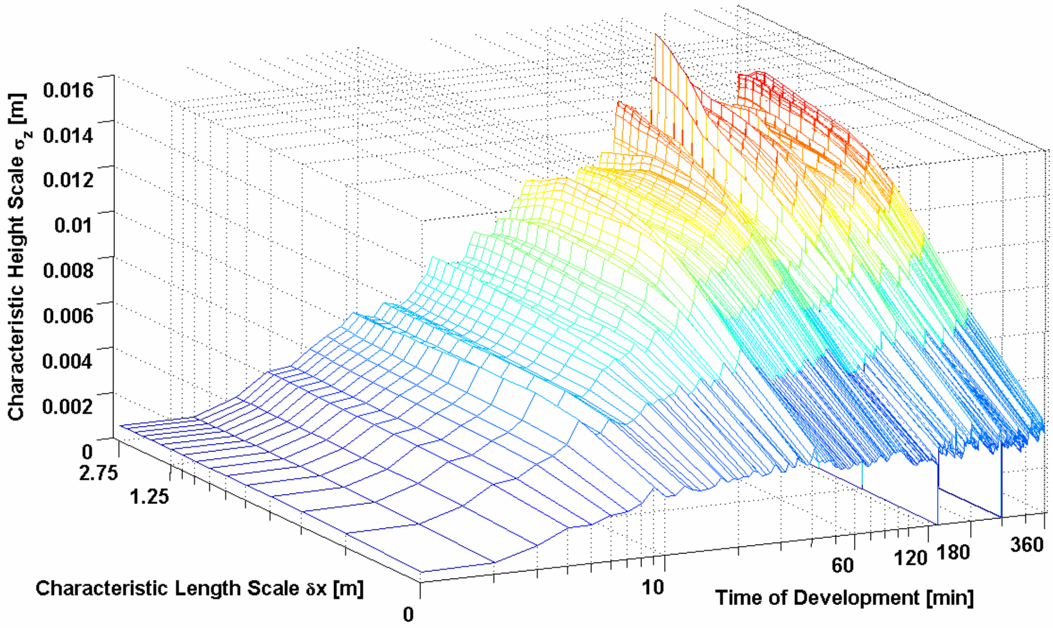

Fig. 1 Display of development of bed-form characteristics σ_z over δx, the characteristic height and length scales for dunes when seen as a random field of sand-bed elevations, for the centreline longitudinal profile in the narrow flume.

3 EXPERIMENTAL INVESTIGATION

The data utilized for this paper are part of SWAT.nz – the Sand Waves and Turbulence research program undertaken in New Zealand (Coleman et al., 2007). The experimental setup and measurement procedure are introduced in a general manner in Friedrich et al. (2005). For this study two experiments with similar flow conditions but carried out in different flumes are analyzed in more detail. Experimental parameters are given in Table 1. The ‘narrow flume’ experiments were carried out in a 12-m-long, 0.38-m-deep and 0.44-m-wide, glass-sided, open-channel flume. The ‘wide flume’ experiments were carried out in a 45-m-long, 1.2-m-deep and 1.5-m-wide, glass-sided, open-channel flume.

The sand in both flumes was first flattened and then exposed to the flow. All mobile bed runs reached equilibrium stages of bed-form development during experiments. Acoustic sensors were utilized (Friedrich et al., 2005) to measure the 3-D development of bed forms.

For analysis purposes, the recorded area can be divided into eight longitudinal profiles along the narrow flume and ten longitudinal profiles along the wide flume.

Run Name	Flume Width	d_{50}	D	T	S_e	U_{avg}	Fr	Re	Recording data				
	[m]	[mm]	[m]	[° C]	[-]	[m/s]	[-]	($x10^3$)	Length [m]	Width [m]	Width [%]	Resolution along [cm]	Resolution across [cm]
nsc175	0.44	0.85	0.15	18	0.17	0.57	0.470	203	6.25	0.175	40	1.25	2.5
wsc115	1.5	0.85	0.15	18	0.43	0.54	0.445	270	18.48	1.35	90	2	15
Note: Kinematic viscosity ν=0.000001-m^2/s; Specific gravity s=2.65; Critical shear velocity 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													

Table 1: Experimental parameters.

4 RESULTS & DISCUSSION

4.1 GROWTH COMPARISON ACROSS THE FLUME

As expected, variability between development of longitudinal profiles across the flume was observed. Figure 2 shows the development of the dimensionless growth σ_z / σ_{z0} for the wide flume (a) and the narrow flume (b). Even though only the central 40% of the narrow flume width were available for analyses, the dimensionless bed-form growth, σ_z/σ_{z0} shows an increase away from the centreline of the flume. For the bed-form growth in the wide flume the differences between developing dunes in the centre of the flume and close to the side walls are 25% for equilibrium height scales (see also Figure 3). Figure 3 shows that equilibrium length scales are of similar size across the flume, therefore indicating a change of steepness caused by different erosion and deposition activities closer to the flume side walls.

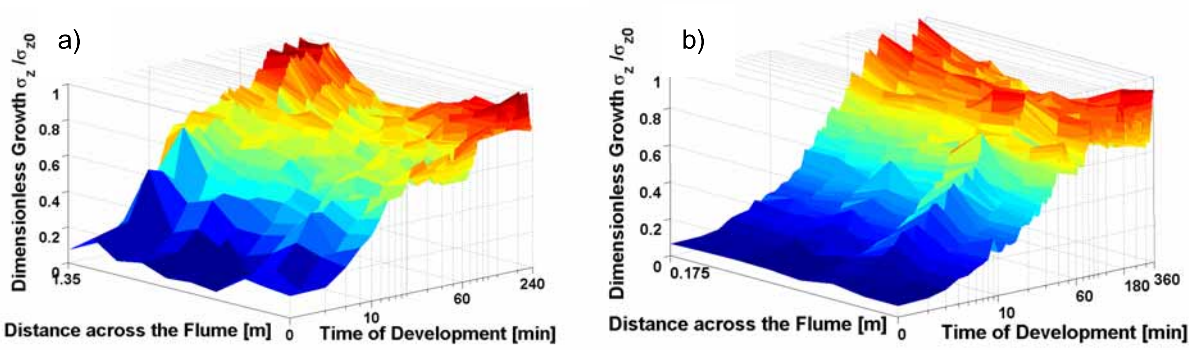

Fig. 2 Comparison of bed-form growth over time across the flume; a) dimensionless growth σ_z / σ_{z0} for the wide flume across 90% of the flume width; b) dimensionless growth for the narrow flume across 40% of the flume width (with σ_{z0} being the max. equilibrium height scale for the whole width of the flume).

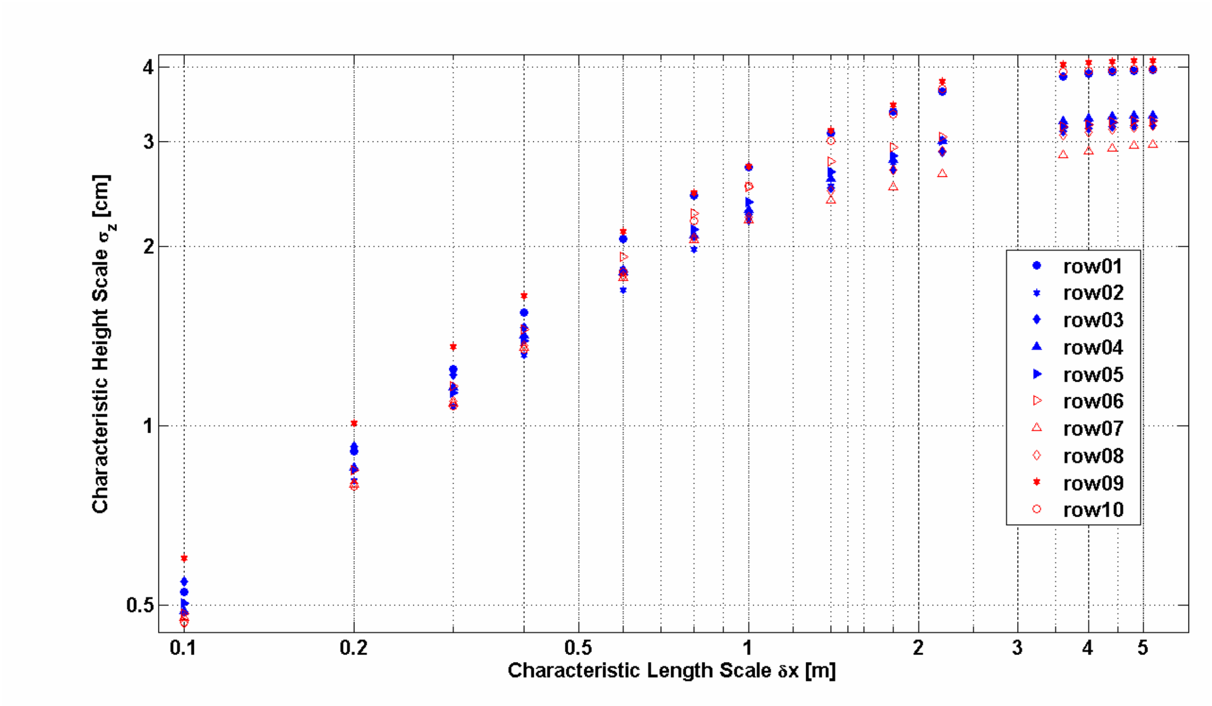

Fig. 3 Comparison of bed-form characteristics σ_z over δx, the characteristic height and length scales for dunes when seen as a random field of sand-bed elevations, for longitudinal profiles along the wide flume at equilibrium.

4.2 GROWTH COMPARISON ALONG THE FLUME

For bed-form-growth experiments from flat bed to equilibrium, it is desirable to observe the seemingly random nature of the initiation of bed forms and the following development from 2-D wavelets into 3-D dunes. However, some researchers argue that 3-D features are undesirable, as they make the conventional 2-D analyses of all processes involved more complicated. Recording windows of different sizes, optimally positioned in the flume, with no disturbances from the hydraulic structures upstream, downstream or from the side walls are required. It is apparent that longitudinal spatial and temporal centreline profiles are least influenced by the flume structure. It is desirable to place the recording window far away from the entrance and exit of the flume so as not to be influenced by it. However, problems arise when sand waves developed upstream of the recording window migrate into it after a certain time. Figure 4 shows longitudinal centreline bed-form profiles along the flume for the wide and the narrow flume during identical stages of development.

Similarly, by visually comparing the longitudinal centreline bed-form profiles for the wide and narrow flumes (see Figure 4), one can see the irregularity of the bed forms in the wide flume (width/depth ratio of 10) caused by their 3-D development. For the narrow flume (width/depth ratio of 2.9), the side walls impose a physical restriction to the lateral spread of the 3-D turbulent flow field as well as the dune development, and crest lines inhabit the whole width of the flume without breaking apart.

Figure 5 shows the 3-D sand-bed elevation plots for the equilibrium state, for both the narrow and the wide flumes. One can clearly see the quasi-periodicity of 2-D dunes across the whole width of the narrow flume, with one dune feature inhabiting an area from one flume-wall side to the other side. Conversely, the wide flume allows the dune bed to develop laterally and crest lines break up across the flume.

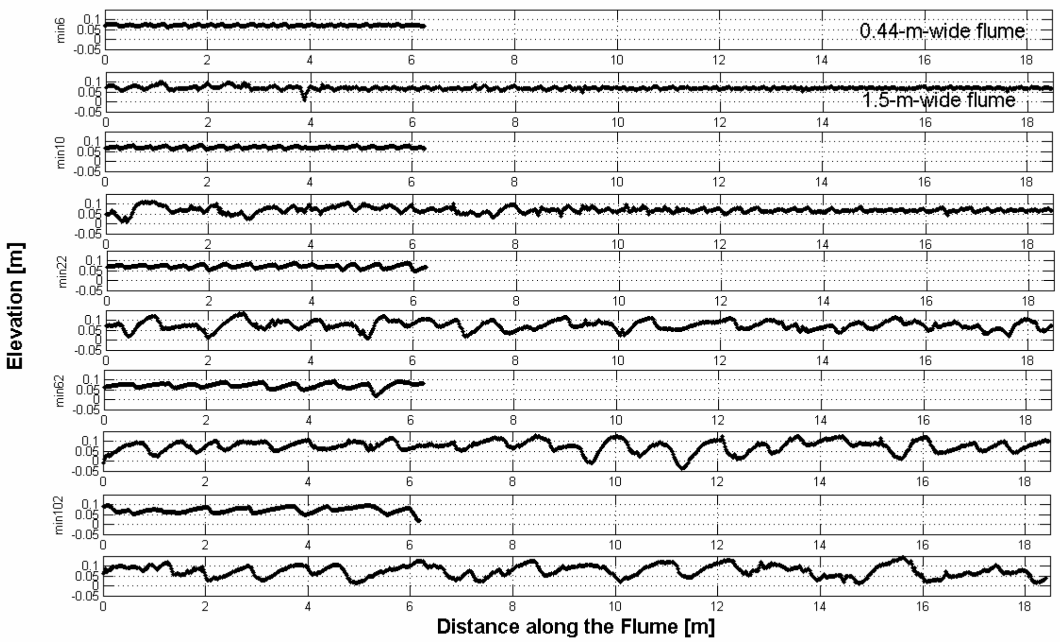

Fig. 4 Comparison of longitudinal centreline bed-form profiles along the flume for the wide and the narrow flumes during different stages of development.

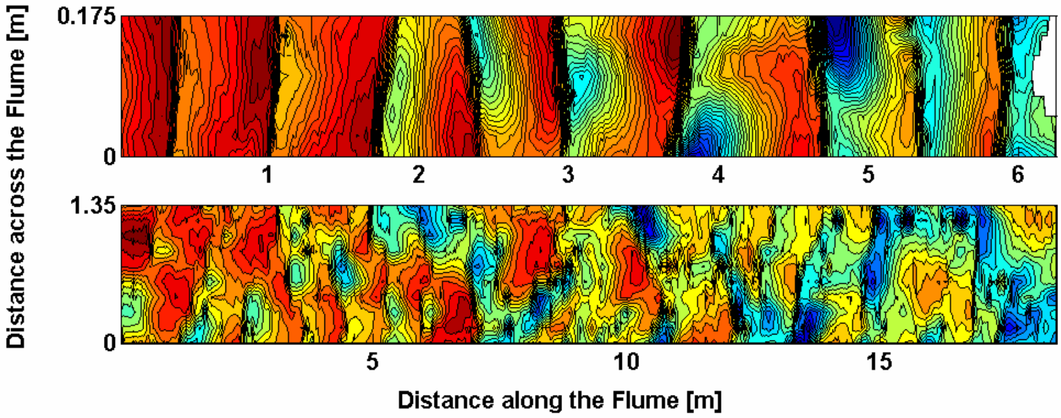

Fig. 5 Comparison of 3-D bed-form profiles for the narrow (top) and the wide (bottom) flumes at equilibrium. Blue indicates a trough and red indicates a crest.

In summary, when analyzing longitudinal centreline profiles, a larger recording window is needed for the wider flume in order to gain accurate averaging values based on the irregular sand-bed elevation field when recording a temporal or spatial series. Larger scale dunes migrating into the recording window from upstream will subsequently change the development of dunes downstream for a limited time span, in this case until around min 20 of development in the wide flume (see Figure 4). However, for the analyzed experiments this disturbance can be neglected for the given flow and sediment conditions and the flume width influence is the important factor for differences in the dune development.

4.3 FLUME COMPARISON

Applying analyses of bed-form growth for random fields as introduced by Nikora and Hicks (1997) shows height and length scaling features are more than 100% larger for equilibrium conditions in the wider flume when compared to the narrower flume (see Figure 6a). The increase in height scaling parameters can be attributed to the longitudinal as well as lateral development of dunes in the wide flume, compared to only minor lateral development in the narrow flume. δx, the characteristic length scale, is also substantially larger for the wide flume, which can be attributed to the irregularity of the dune field along the flume (see Section 4.2). For the wide flume it is necessary to include a larger amount of data in order to obtain a saturated characteristic height scale, σ_z, for stages during development.

Figure 6b) shows the scaling relationship from Eq.2 applied to selected data during development. It shows that dimensionless scaling, in the form of utilizing equilibrium parameters for characteristic height, length and time scales, gives a better agreement, but still shows differences for longitudinal profiles closer to the flume side walls (rows 1,2 and 9,10; compared to rows 5 and 6 in the centre of the flume).

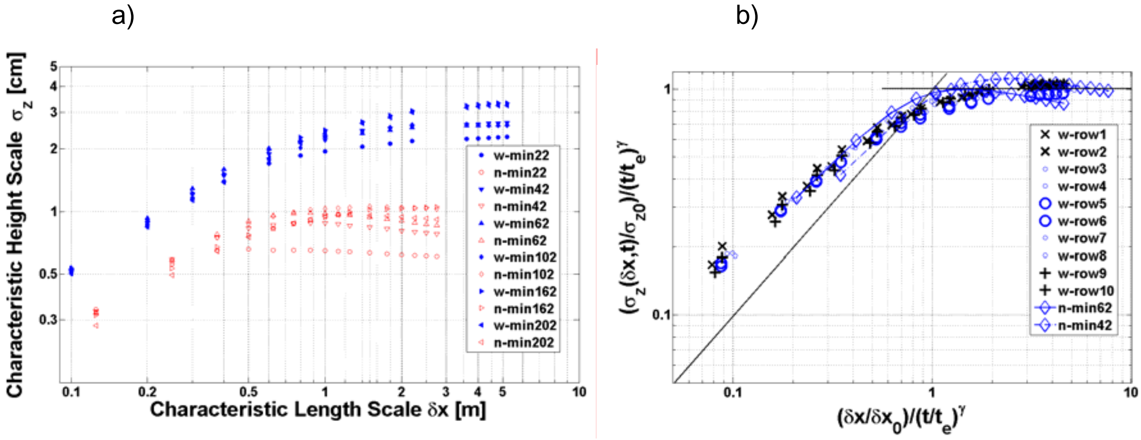

Fig. 6 a) Comparison of bed-form characteristics σ_z over δx, the characteristic height and length scales for dunes when seen as a random field of sand-bed elevations, for the centreline longitudinal profile for both flumes; b) Applying scaling Eq.2 for selected data during development (for all longitudinal profiles along the flume for minute 80 for the wide flume, and centreline profiles for minute 42 and 62 for the narrow flume).

5 CONCLUSIONS

The present study was conducted to investigate similarity issues in flume measurements for dunes developing from a flat bed. From a comprehensive data set, two experiments displaying similar conditions but undertaken in different flumes are analyzed in more detail. Sand-bed elevation fields are treated as random fields rather than discrete sand waves.

It is shown that dunes in the wider flume display larger height and length features. The side-walls in the narrower flume restrict the 3-D behaviour of the flow field and therefore also restrict the lateral development of the dunes. Height and length scaling features are more than 100% larger for equilibrium conditions in the wider flume when compared to the narrower flume. Normalizing the dune development with equilibrium size and time parameters shows a better agreement for the data analyzed.

For the wide flume data (which were measured over 90% of the flume width) it is shown that the side wall significantly influences the dune development near the wall, when compared to the centreline profile. Only the central 30% of the width of the wide flume exhibits similar height/length scales to those of the centreline profile itself. This is supported by the data from the narrow flume, where only a three-dimensional strip of the centre 40% of the narrow flume was recorded.

In summary, different flume structures can influence dune development differently. Quantitative growth parameters can differ for different flume environments, even if the flow and sediment conditions are the same. Dimensionless scaling, in the form of equilibrium parameters, enable better comparison of qualitative growth of bed forms. However, bed forms close to the flume side walls exhibit different geometries, because the walls act as hydraulic structures, inducing different erosion and deposition activities and influencing the dune development.

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