STATISTICAL ANALYSIS OF BEDFORMS DEVELOPED UNDER UNIDIRECTIONAL FLOW

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Abstract A set of developing dune experiments from a flattened sand bed has been obtained in a narrow 0.44-m-wide and 12-m-long glass-sided open channel. The sand in use is a coarse uniform sand of D_{50}=0.85-mm. The chosen flow depths generated practically 2D dunes in flow direction over the length of the channel. Spatial sand-bed-elevation profiles have been recorded in the centreline of the flume over a distance of 6-m, roughly every 23-sec over the time of development. The statistical properties of a series of bed elevations are analysed with both a discrete and a continuous approach. Previous analysis showed that the continuous approach provides more objective results, but interpreting the results of the analysis requires careful consideration. In this paper, results from the comparison of bedform statistics with flume and flow characteristics under which the bedforms were developed, are presented. When comparing the statistical bedform properties with the ratio of flume width to flow depth, b/h, it is shown that a relationship exists for the available data. The input data for this study is limited, but the presented results show that more attention needs to be given to the flume environment, in which bedforms are developed. For this study dimensionless bedform properties vary up to 20%, displaying a correlation with flume width/flow depth ratio.

Keywords Sediment transport; Bedform; Dune; Flume width; Statistical analysis.

1 INTRODUCTION

River bedforms are the result of a feedback mechanism between the flow of water and a movable sediment bed. Through bedforms enormous amounts of sediment are transported downstream to oceans. Past studies provided vast insights into the relationship of flow properties (flow depth and flow velocity) and discrete bedform dimensions (height and length).

The determination of the topographical characteristics of the bed surface is important for forecasting the growth of dunes under different flow conditions and modelling alluvial channel processes. As dunes strongly influence the hydraulic roughness and the sediment transport, a quantitative description of dunes is vital in providing relationships between the dune parameters and the hydraulic conditions.

Friedrich et al. (2007) discussed current methods for quantifying hydraulic roughness of river dunes generated in laboratory environments. They can be distinguished into two groups: a) discrete approach (also called direct approach); b) continuous approach (also called indirect or random-field approach). Commonly, the discrete approach is applied in determining geometric characteristics such as height and length of dune profiles. When applying the continuous approach, dune profiles are treated as a random field of sand-bed elevations.

One goal of bedform research is to be able to simulate and predict bedform development for known environments. Thus characteristics of the turbulent flow need to be known as well. According to Nezu (2005), our understanding of turbulence in 2D open-channel flows has been investigated since the 1970s, but studying the 3D flow features, such as secondary currents, only date back 20 years ago. Nezu et al. (1989) showed that for small ratios of flume width to flow depth, the maximum velocity does not occur on the water surface, but below. Nezu and Nakagawa (1993) summarise that a critical ratio of flume width to flow depth, b/h_{crit}~5 exists for smooth channels. For ratios of flume width to flow depth less than 5 no idealised 2D time-averaged flow characteristics can be obtained and the effect of secondary currents needs to be taken into account (Figure 1). No study is known to the author where a critical ratio of flume width to flow depth is obtained for channels covered with bedforms.

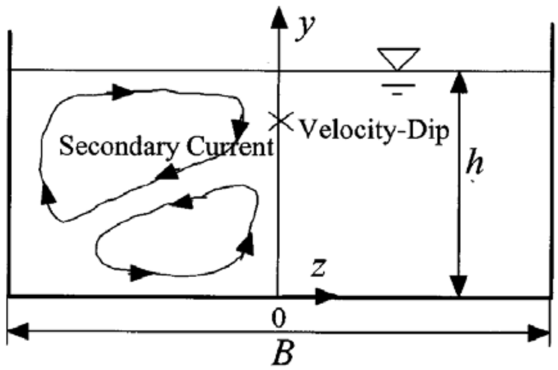

Fig. 1 Secondary currents (Nezu and Nakagawa, 1993)

When studying literature of laboratory investigations of bedform development, most experiments are undertaken with a ratio of flume width to flow depth less than 5. Thus the question arises, how does the width/depth ratio of flume environments influences 3D bedform properties?

Williams (1970) studied the effect of flume width and flow depth on bedform characteristics. He showed that dune heights increase with channel width, for constant depth. Although for some tests, undertaken with certain flow depths, no change in dune height was observed. Williams (1970) did not make suggestions of how the ratio of flume width to flow depth might influence the varying observations.

Crickmore (1970) wrote that experimental statistical bedform characteristics vary and provided two main reasons. Firstly, the absence of standardized procedures for obtaining geometric bedform information. Secondly, the influence of flume width for laboratory experiments studying bedform geometries. Discussion of the former aspect is covered in Friedrich et al. (2007). Studying the latter aspect, Crickmore's (1970) work showed that although bedforms displayed similar features for different ratios of flume width to flow depth, closer examination showed a correlation between bedform characteristics and flume width. Crickmore's (1970) study concentrated on the influence on the flume width alone and did not take into account the ratio of flume width to flow depth and how flow structures might influence bedform development.

The objective of this study is to use the results of a previous dune characteristics analysis, obtained through application of different analytical methods, for studying the effect of flume width/flow depth ratio on dune characteristics. The absence of standardized procedures for obtaining geometric bedform information is discussed in a previous paper (Friedrich et al., 2007) and will be only briefly mentioned herewith. For this paper the experimental setup and analysis are described in essence. The results are compared to the ratio of flume width to flow depth and observations are discussed.

2 EXPERIMENTAL SETUP

A data set of developing dune bedforms from a flattened sand bed was obtained at the Fluid Mechanics Laboratory at The University of Auckland. The experiments were conducted in a 12-m-long, 0.38-m-deep and 0.44-m-wide glass-sided open-channel flume. Water is recirculated, as well as the sediment. The sediment in use is a coarse (D_{50}=0.85-mm) filter sand.

2D centreline bed profiles were measured over a distance of 6-m. The streamwise position was recorded at 2.45-mm distance increments, accuracy of measurement being ±1.23-mm. Bed profiles were recorded roughly every 23-sec for each experiment, lasting between 2.5 and 10 hours.

The mean depth-averaged flow velocity for each experiment was estimated by utilizing ADV flow measurements in the upper part of the water column, at the start of each experiment (with flat bed).

All together a set of 24 experiments were recorded, of which 14 experiments started with a flattened bed and were exposed to steady uniform flow conditions. The remaining 10 experiments were part of a flood-wave research project and a PIV flow-field study and will not be discussed herein. The experimental conditions for the experiments discussed are given in Table 1.

3 ANALYSIS

The experimental data is analysed with two different approaches: a) the discrete approach (also called direct approach); b) continuous approach (also called indirect or random-field approach). More information on the analysis and discussion of the results can be found in Friedrich et al. (2007).

Table 2 shows the equilibrium values of characteristic height and length data obtained through the continuous analysis as well as the average dune height and length as obtained through the discrete analysis.

4 RESULTS AND DISCUSSION

The experimental dune data is evaluated in regards to its correlation with the ratio of flume width to flow depth. All experiments are undertaken in the same flume environment, but flow depth varies for different tests. The ratio of flume width to flow depth is in the range of 2.9 to 4.5. Therefore below the critical value suggested by Nezu et al. (1989) of 5 for smooth channels. Based on the previous studies by Williams (1970) and Crickmore (1970), it can be expected that dune characteristics will vary over that range. For both the continuous approach as well as the discrete approach, dimensionless dune characteristics are plotted against the ratio of flume width to flow depth (Figures 2 and 3). Bedform characteristics (height and length) are made dimensionless in regards to flow depth.

Figure 2 shows the relationship between bedform properties obtained with the continuous approach and the flume width/flow depth ratio. Minor trends can be seen for both values, dimensionless characteristic height and length. The dimensionless characteristic length is increasing with increasing ratio of flume width to flow depth. Whereas the dimensionless characteristic height is slightly decreasing with increasing ratio of flume width to flow depth. The steepness, ratio of height to length, is also slightly decreasing with increasing ratio of flume width to flow depth.

Flow Conditions	Experiment Names	Flow parameters										
		B	Q	q	H	B/H	S_b	U	Fr	Re	$u_*^{(1)}$	$u_*^{(2)}$
		[m]	[l/s]	[m^2/s]	[m]	[-]	[-]	[m/s]	[-]	[-]	[m/s]	[m/s]
I	T3,T8	0.44	29.42	0.0669	0.1250	3.52	0.0010	0.53	0.48	66788	0.035	0.032
II	T6,T23	0.44	35.94	0.0817	0.1250	3.52	0.0015	0.62	0.56	77604	0.043	0.036
III	T4,T7,T11	0.44	38.56	0.0876	0.1250	3.52	0.0020	0.70	0.63	87633	0.050	0.041
IV	T5,T24	0.44	27.19	0.0618	0.1000	4.40	0.0015	0.58	0.58	57709	0.038	0.035
V	T13	0.44	20.46	0.0465	0.1000	4.40	0.0010	0.47	0.47	46508	0.031	0.028
VI	T14	0.44	31.47	0.0715	0.1125	3.91	0.0015	0.62	0.59	69975	0.041	0.037
VII	T15,T22	0.44	43.74	0.0994	0.1500	2.93	0.0015	0.65	0.54	97463	0.047	0.037

B = flume width, Q = discharge, q = specific discharge, H = water depth, S_b = initial water surface and bottom slope, U = average flow velocity, Fr = Froude number = U/sqrt(gH), Re = Reynolds number = UH/ν, Kinematic viscosity ν=0.000001-m^2/s, u_* = shear velocity, with $u_*^{(1)}$=sqrt(gHS_b), and $u_*^{(2)}$=based on ADV measurements
Note, for experiment T22,T23,T24 the downstream water depth was changed during the experiment, such that the water-surface slope was approximately equal to the bed-surface slope; for the other experiments the downstream water level was kept constant to the initial value

Table 1 Relevant hydraulic parameters of the experiment.

Experiment Name	Flow conditions	Rec. Profiles	Development Time	H	B/H	Equilibrium bed-form characteristics Bed-form geometry (continuous) Char. Height	Char. Length	Steepness	Dimensionless Char. Height	Dimensionless Char. Length	Bed-form geometry (discrete) Height	Length	Steepness	Dimensionless Height	Dimensionless Length
		[-]	[hrs]	[m]	[-]	[cm]	[cm]	[-]	[-]	[-]	[cm]	[cm]	[-]	[-]	[-]
T3	I	563	3.50	0.125	3.52	0.71	112	0.0064	0.057	8.958	2.5	67	0.038	0.202	5.365
T4	III	412	2.53	0.125	3.52	0.83	99	0.0084	0.067	7.938	2.9	54	0.054	0.231	4.295
T5	IV	391	2.44	0.100	4.40	0.53	90	0.0059	0.053	9.041	2.6	60	0.043	0.257	6.019
T6	II	482	3.03	0.125	3.52	0.90	130	0.0070	0.072	10.367	2.9	50	0.057	0.228	4.034
T7	III	325	3.02	0.125	3.52	0.64	100	0.0064	0.051	7.975	3.2	54	0.059	0.253	4.289
T8	I	524	3.60	0.125	3.52	0.79	111	0.0071	0.063	8.900	2.8	75	0.038	0.227	5.991
T11	III	458	2.92	0.125	3.52	0.91	159	0.0057	0.073	12.749	3.2	63	0.051	0.256	5.050
T13	V	1137	8.57	0.100	4.40	0.67	144	0.0046	0.067	14.369	2.3	65	0.036	0.233	6.539
T14	VI	1496	9.72	0.1125	3.91	0.77	96	0.0080	0.068	8.565	2.6	58	0.044	0.229	5.182
T15	VII	676	4.39	0.150	2.93	1.12	158	0.0071	0.074	10.519	3.4	62	0.055	0.228	4.144
T22	VII	455	2.90	0.150	2.93	1.48	161	0.0092	0.099	10.745	4.1	67	0.061	0.273	4.497
T23	II	503	3.26	0.125	3.52	1.33	126	0.0106	0.107	10.099	3.6	69	0.052	0.288	5.509
T24	IV	575	3.74	0.100	4.40	1.07	149	0.0072	0.107	14.924	3.2	60	0.052	0.317	6.044

Table 2 Statistical dune parameters.

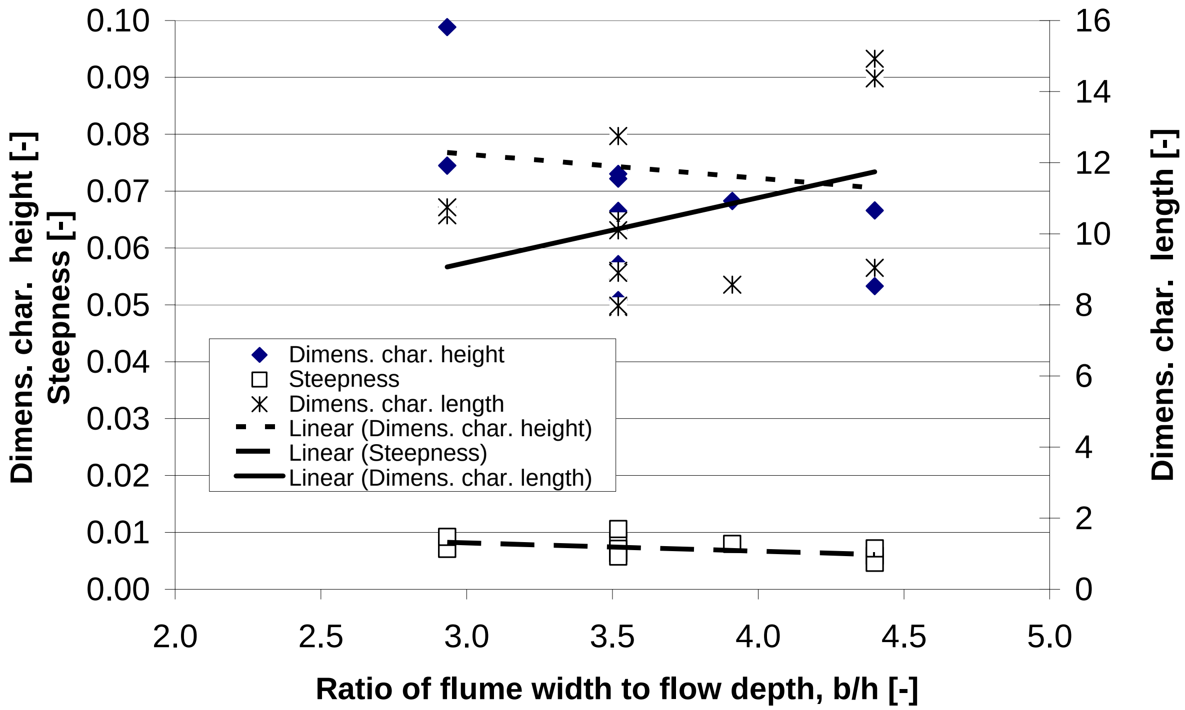

Fig. 2 Ratio of flume width to flow depth vs. dimensionless characteristic bedform properties.

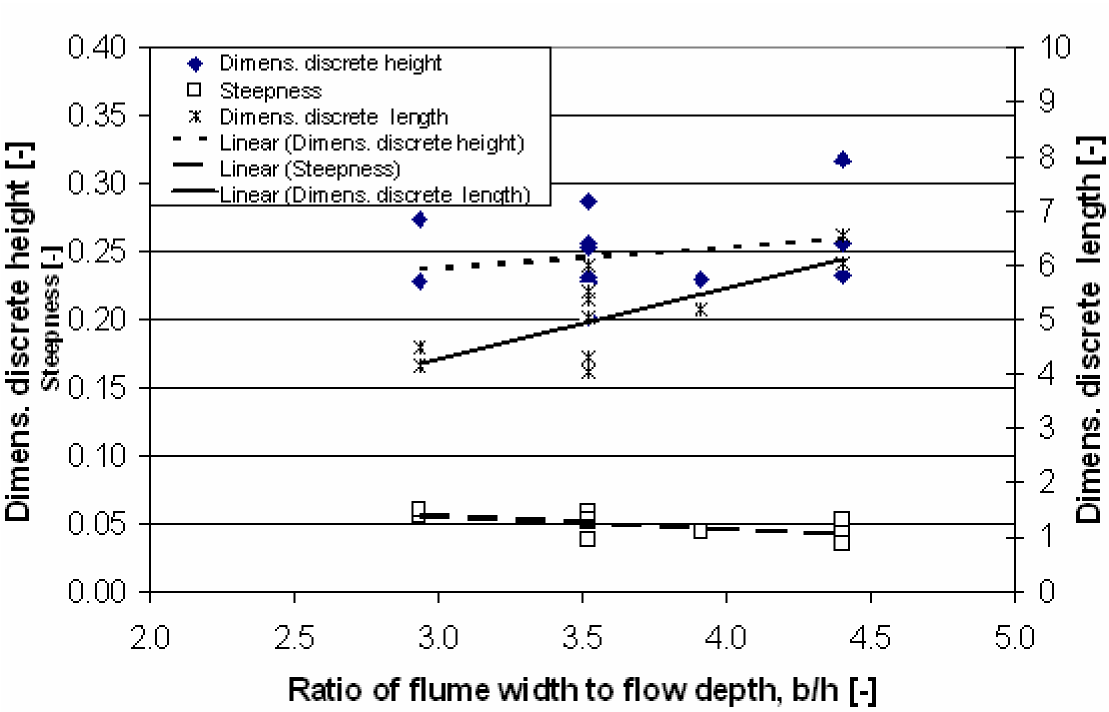

Fig. 3 Ratio of flume width to flow depth vs. dimensionless discrete bedform properties.

The interpretation of the qualitative values is difficult, as it can not be compared with previous laboratory data analysed with the continuous approach.

Figure 3 (evaluating data obtained when applying the discrete approach) displays similar trends to Figure 2. However, Figure 3 shows that the dimensionless discrete height increases slightly with increasing ratio of flume width to flow depth, compared to a decrease for the height characteristics obtained through the continuous approach. It seems that bedform length properties are more dependent on the flume width/flow depth ratio than bedform height properties, for both analytical approaches. Figure 3 also shows that dimensionless discrete bedform properties approach h/3 for average dune height and 6h for average dune length (Yalin and Da Silva, 2001) with increasing flume width/ flow depth ratios.

5 CONCLUSION

Using experimental data to improve modelling of bedform development simulations shows the need to study the factors which influence the growth development of bedforms. Studies concentrate on the influence of flow field and flow depth on the bedform development. Often the influence of flume width is neglected, and it is assumed that recorded 2D centreline profiles are formed under interaction with 2D flow.

In this study, statistical bedform data, previously obtained with two different analytical approaches, the discrete and the continuous approach, are evaluated in regards to correlation with ratio of flume width to flow depth.

The results show that a correlation exists between bedform characteristics and width/depth ratio and the main trends are similar for data obtained through applying the two different statistical approaches. Although dune height properties are decreasing slightly with increasing width/depth ratio for data obtained through the continuous approach. The trend shows an opposite direction when evaluating dune height properties obtained through the discrete approach.

In summary, the study shows that for the tested scenario (width/depth ratio between 2.9 and 4.5) dimensionless dune characteristics are dependent on the width/depth ratio and can change up to 20%.

Given the limitations of the study, it is necessary to include more experimental data in the analysis in order to obtain a more accurate correlation model.

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REFERENCES

Crickmore, M. J. (1970). "Effect of Flume Width on Bed-Form Characteristics." Journal of the Hydraulics Division, 96(HY2), 473-496.

Friedrich, H., Paarlberg, A.J. and Lansink, J. (2007). "Evaluation of statistical properties of dune profiles." In: Dohmen-Janssen and Hulscher (Eds.), Proc. of the 5th IAHR Symposium on River, Coastal and Estuarine Morphodynamics, Enschede, The Netherlands, 2, 913-921. Taylor & Francis Group, London.

Nezu, I., and Nakagawa, H. (1993). "Turbulence in open-channel flows."

Nezu, I. (2005). "Open-channel flow turbulence and its research prospect in the 21st century." Journal of Hydraulic Engineering, 131(4), 229-246.

Nezu, I., Nakagawa, H., and Rodi, W. (1989). "Significant difference between secondary currents in closed channels and narrow channels." Proc., 23rd IAHR Congress.

Williams, G. P. (1970). "Flume width and water depth effects in sediment-transport experiments." U.S. Geol. Surv., Prof. Pap. 562-H, 37.

Yalin, M. S., and Ferreira Da Silva, A. M. (2001). Fluvial Processes, Delft, The Netherlands.