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Discussion on bedform data recording, post processing and analytical suitability

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ABSTRACT: Acoustic sensors, and more recently laser and photographic methods, are often used to obtain topographic information of underwater features in the laboratory. This physical quantity can vary with time or space. As with every signal, limitations of the measuring device or unfavorable environmental conditions can influence the quality of the signal. Studies undertaken by the authors in recent years highlight the new challenges that modern high-resolution datasets provide for identifying geometric bedform features. There is a need for a unified automatic post-processing methodology guideline. In the past, bed elevation datasets had a low data range, often allowing straightforward determination of discrete bedform parameters by observations only, or limited analysis. Examples from experiments undertaken in a narrow flume with 0.44-m width and a wide flume with 1.5-m width, highlight the new post-processing requirements needed for modern high-resolution datasets, which can easily exceed 1-million data points per bedform profile. Finally, a discussion is presented on the data specification needs for bedform analysis.

1 INTRODUCTION AND OUTLINE

The foremost objective of this paper is to present the challenges associated with recording and analyzing modern high-resolution datasets of bed elevations, such as used for studying bedform development from a flattened sand bed to equilibrium. Modern datasets, recorded in live-bed conditions, exposed to sometimes high suspended sediment concentrations in the wake of bedforms, are needed to better understand why bedforms transfer from ripples to dunes, or go through a transition from 2D features to 3D features (Venditti et al., 2005), and how coalescence theories (Coleman and Melville, 1994, Raudkivi and Witte, 1990) can be applied in 3D. Analyses of how 3D profiles change over time are needed. Those profiles represent quasi-4D datasets (3D surfaces changing over time).

Acoustic sensors are generally used to obtain topographic information of underwater features. In essence, a signal that can be used to describe the underwater features is recorded. This physical quantity can vary with time or space. As with every signal, limitations of the measuring device or unfavorable environmental conditions can influence the quality of the signal. It is important to define those limitations and to use the measuring device in environments which are suitable for its operation. In addition, signal properties, such as sampling frequency and length, should be aligned to fit the proposed analysis demands. In regards to bedforms, the post-processed data series used for any analysis should represent the bedforms as accurately as possible.

During live-bed data acquisition, especially in high flowrates, where it is not uncommon for larger particles to be suspended in the wake of bedforms, datasets become increasingly noisy. Thus, individual particles or a cluster of particles in suspension, with a combined diameter equal to or greater than the sound wavelength, will be picked up as a data point by the acoustic sensor (Richardson et al., 1961).

In the following sections, properties of some of the major datasets are reviewed, analytical approaches are presented, and post-processing procedures of high-resolution velocimeter data are used to show the importance of a more streamlined post-processing guideline for bedform datasets.

2 BEDFORM DATASET RECORDING

In general, bedform features are studied by obtaining elevation records z in respect to space $z(x)$ or time $z(t)$. It is shown that for laboratory studies both types of records display stationary Gaussian processes (Nordin, 1971), a characteristic for natural processes, which are influenced by random factors. Spatial bed records exhibit a lag during the recording, with the lag assumed to be small enough compared to the change of the bed during that time. Those spatial records are generally used to obtain height and length distributions, whereas temporal records allow the direct extraction of height and bed period distributions.

2.1 *Past major datasets*

Most of the major experimental laboratory datasets have been recorded as spatial or temporal longitudinal centerline profiles in a flume. There exist several major datasets of recorded bedform geometry; a few of them are introduced briefly below.

Guy et al. (1966) used visual and photographic means to record the general bed configuration at the end of an experiment on the drained bed, with the help of an observation window. In addition, a depth sounder (Richardson et al., 1961) was used for most of the experiments, either obtaining spatial bedform profiles by traversing the length of the flume, or temporal profiles by recording bedforms moving past a stationary probe. Length, height and celerity information were obtained, which are stated to represent the mean values plus or minus 10 percent.

Williams (1970) used point-gauge measurements every 1.2-m, over a length of 14-m to measure the bed surface. Thus, three to ten bed features were identified and averages were taken to obtain height information. Crests were counted along the whole flume test section, and length features were obtained by dividing the measurement length by the number of crests. Bedform celerity information was also obtained by individually tracking the downstream movement of one to six bedforms over a known distance, and averaging that information.

Nordin (1971) obtained 54 bedform records in flumes ranging from 0.22-m to 2.6-m width, and an artificial channel of 18.3-m width. For all but the narrowest flume, a bed profiler (Karaki et al., 1961) was used to obtain spatial and temporal bed elevation records. The spatial resolution varied mainly between 25-mm and 110-mm, with a measurement frequency of 1-min for the temporal recording.

Costello and Southard (1981) used a point-gauge to measure the bed surface. Doing so required them to drain the flume at the end of each experiment. The measurement resolution was 10-mm, and measurements were taken along the centerline in the downstream half of the flume.

Klaassen (1990) obtained bedform information as part of a wider study on the effect of gradation on hydraulic roughness. Three longitudinal spatial bed profiles were obtained, with a sampling resolution of 10-mm, over a length of 30-m. Measurements were undertaken during several stages of the study. Some temporal measurements also were taken, allowing the calculation of celerity values.

Baas (1994) studied the development of ripple bedforms with the help of flume wall drawings, photographs and video of bedform features. For the drawings, 30 seconds were needed to complete a spatial profile. Ripple heights and lengths were obtained as the vertical distance between crest and trough, with the length being the horizontal distance between successive crests. Five to 40 individual ripple features were used to calculate average values.

To note, all those datasets presented underwent limited post-processing procedures (at least not discussed in detail in the publications), compared to the post-processing features required for the modern high-resolution datasets. Besides some of the datasets from Nordin (1971), most of the records would not be suitable for detailed analysis of the dynamic changes between profiles, such as comparing the temporal change of spatial profiles, or comparing the spatial change between temporal profiles. One would not be able to go back, and apply a unified methodology to obtain height and length features for all datasets, as the underlying information is partly missing.

Using newly available technology, Venditti (2003) more recently obtained a 3D dataset of developing bedforms with the help of top-view video recording, but at the same time used a stationary echo-sounding probe to record temporal bed profiles.

2.2 *Modern high-resolution datasets*

There is the need to record the change of bed elevation over an area, and thus study the change of Digital Elevation Models (DEM) over time, quasi 4D datasets. In addition, data needs to be recorded in live-bed conditions, reflecting the dynamic nature of the mobile bed, thus not interrupting the experiments for data capture. Such a dataset was obtained by the authors (Friedrich, 2010). The chosen instrument was an array of 32 Multiple Transducer Arrays (MTAs) from Seatek (Friedrich et al., 2005). Using a moving sensor arrangement allowed to obtain spatial DEM's of bed features and recording their development over

Figure 1. Photo of the MTA arrangement in the wide flume, with projection of the recorded data grid.

time (Fig. 1). For bedform studies undertaken with fine sediment, a high suspended sediment concentration is present for faster flowrates. For such tests, a robust post-processing technique must be in place to de-noise data, whilst still maintaining the integrity of the measured bed surface.

2.3 *Analytical suitability*

For most of the past datasets, the analysis concentrated on height, length and celerity information, for individual bedforms or averaged for a series of either temporal or spatial data profiles. Due to the nature of visual data recording, and associated lack of information between identified crest and trough locations, it is not possible to go back to most of the past datasets and re-apply new analysis methods.

One problem that is encountered in most bedform studies is the use of a multitude of methods to determe heights and lengths. The discrete approach (see Section 3.1) is the basis of most of the analysis of the datasets as presented in Section 2.1, with Nordin (1971) being one of the pioneers to treat bed elevations profiles as random fields (see Section 3.2).

In contrast, datasets obtained by the authors over the last years, amongst them the one presented in Section 2.2, are suitable for discrete approach analysis, as well as the continuous approach analysis, which requires the signal to be a continuous sequence of discrete values, thus allowing identification of saturation and periodicities at various scales.

The following section describes the analysis differences in more detail.

3 BEDFORM ANALYSIS

Friedrich et al. (2007) studied the relationship of dune statistics between the discrete and the continuous approach on a set of development experiments in a narrow 0.44-m-wide and 12-m-long glass-sided open channel. It is shown that the continuous approach provides more objective results, but interpreting the results of the analysis requires careful consideration. In the following, problems associated with the subjective interpretation of discrete bedform analysis are summarized.

3.1 *Discrete approach*

For applying the discrete approach, a bedform can be described by signals of varying sampling resolution, as long as crest and trough locations are clearly identifiable (Fig. 2). Obtaining discrete height and length features, based on various means

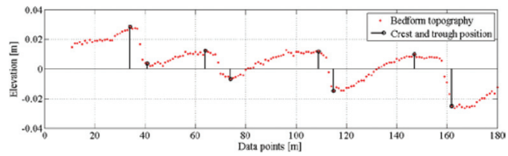

Figure 2. Bedform represented by crests and troughs. Having only the location of crests and troughs provides sufficient information about commonly used height and length of bedforms.

to identify crest and trough locations, through visual observations (eye, drawing, photo and more recently video) or low-resolution mechanical means (as referred to in Section 2.1) often results in manual and subjective determination of those bedform geometries. van der Mark and Blom (2007) provided a detailed overview of a bedform tracking tool, highlighting the problem of the existence of a multitude of methods or numerical codes for bedform characteristics. van der Mark and Blom's (2007) bedform tracking tool, which is suitable for discrete analysis, can be used for both laboratory and field data.

The most common discrete analysis approaches for determination of height and length features are based on crest and trough identification:

- Subjective visual determination of crest and trough location, such as observing mobile beds through the flume side walls.
- Zero-crossing method. Initially, the zero-crossing locations are identified. The maximum elevation data point between successive zero-crossings is the crest, and the minimum elevation is the trough. Alternatively, up-crossing or down-crossing locations can be used.
- Lee-slope method. Identifying lee-slope locations, which requires setting subjective thresholds of minimum detectable bedform height, bedform length and number of data points to make up the lee slope. The maximum elevation data point between successive lee slopes is the crest, and the minimum elevation is the trough.
- Direct extrema identification. By identifying local maxima/minima, and setting a threshold for which surrounding data points are lower or higher.

As one can see, all methods of identification of crest and trough locations require a subjective input by the researcher, which is the biggest drawback of the discrete approach, and makes it so difficult to compare confidently older datasets.

3.2 *Continuous approach*

For applying the continuous approach, a signal has to be a continuous sequence of discrete

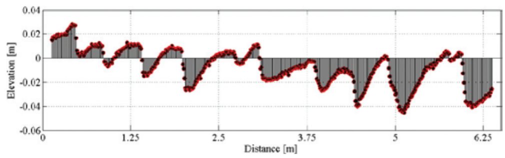

Figure 3. Bedforms represented by continuous signals.

values (Fig. 3). One has to take into account that most patterns in nature, such as the topography of bedforms, are continuous, but signals representing those patterns are limited by the sampling resolution. Therefore the question arises, what sampling frequency and length should be chosen for a complete representation of a pattern? For laboratory bedform environments, often that decision is made ad-hoc, depending on the flume and measurement device capability. In general, a higher sampling frequency allows for a more accurate description of a bedform. Depending on the accuracy of the signal and the size and shape of the measured bedforms, a high sampling frequency can also have the undesired effect of polluting data. Take for example the ripple initiation process, where undulations of less than 10-mm are encountered. Recording such phenomena with a measuring device of ±1.00-mm accuracy, will add considerable noise to the recorded signal, which needs to be taken into account during the analysis and discussion of the results.

The most common continuous analysis approaches for determination of equivalent height and length features are:

- Standard deviation to determine characteristic height parameters.
- Auto-correlation to determine characteristic length parameters.
- Spectral analysis to determine characteristic wave frequency parameters.
- Cross-correlation to determine celerity information.

3.3 *Sampling requirements and data needs*

The following conditions need to be taken into account when designing the recording setup for bedforms intended for continuous analysis:

- *Migration speed of bedforms*: between measurement cycles, the migration should be less than one bedform length (Fig. 4).
- *Sediment transport*—intensity of bed-load and suspended load: influence quality of data (Fig. 5);
- *Bedform shape*: bedforms often have a sloping upstream face and a steep downstream face, thus the sampling interval needs to be small enough to describe steep downstream faces accurately (Fig. 6);
- *Bedform size*: bedforms should be accurately represented—a simple tool to describe accurate presentation could be the ratio of data points per individual bedform (Fig. 7).

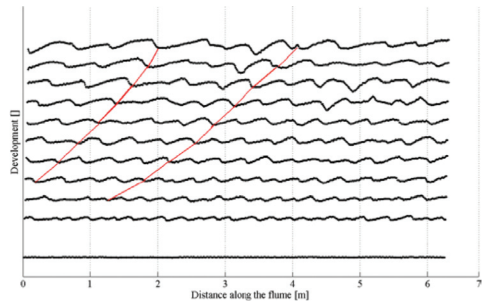

Figure 4. Qualitative development of spatial bed profiles over time.

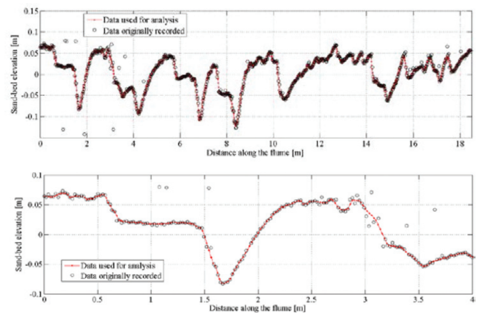

Figure 5. Representation of noise in the recorded data, for a complete spatial profile (top) and for a zoomed-in 4-m section (bottom).

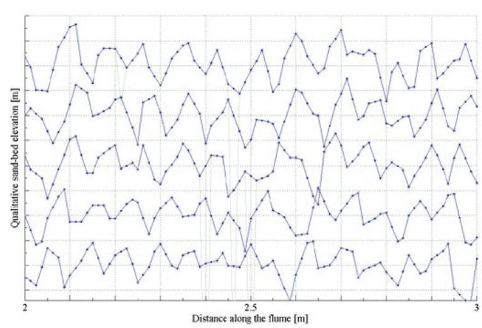

Figure 6. Representation of limited data to identify the shape of smaller bedforms—for developing bedforms. Original data in grey, with overlay of post-processed data.

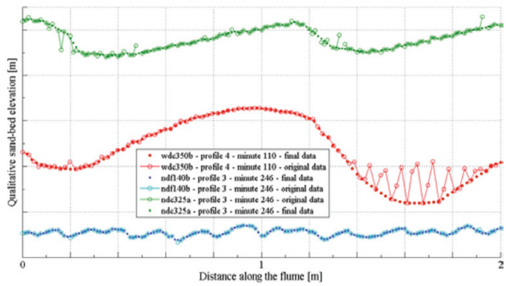

Figure 7. Size comparison of studied bedforms.

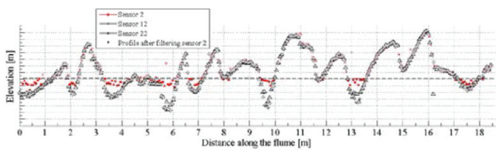

Figure 8. Spatial bed profile, highlighting faulty signals for probe 2, with individual threshold line.

4 BEDFORM DATA POST-PROCESSING

Decisions made during each post-processing step might influence the final representation of bedforms adversely. Most commonly, noise in bed elevation datasets is either the pickup of suspended particles in the systems or equipment noise. During the collection of Friedrich's (2010) dataset, noise was frequently encountered in high flowrates due to the fact that the sensitivity of the measurement instrument was reduced to lower the signal pickup of suspended particles, but doing so increased the chances that the bedload particles were also not detected by the signal. Equipment tests had to be undertaken to determine the most suitable voltage setting for the MTAs for varying flowrates and mobile bed properties. In addition, using multiple probes, which are run from one controller, increases the risks of noise if one or several of the probes are faulty. For Friedrich's (2010) dataset, the following post-processing methodology was set in place:

- Probe signal check. This involves the removal of communication errors, through identification of upper and lower bed thresholds. In addition, for individual faulty probes, individual thresholds were identified (Fig. 8).
- Single-point despiking. Derivatives are calculated for each longitudinal profile. Where slopes at adjacent points are large, nearly equal, and of opposite sign, data points are treated as erroneous spikes and replaced by linear interpolation (Fig. 9). This technique is based on work by Goring and Nikora (2002) on velocimeter data.

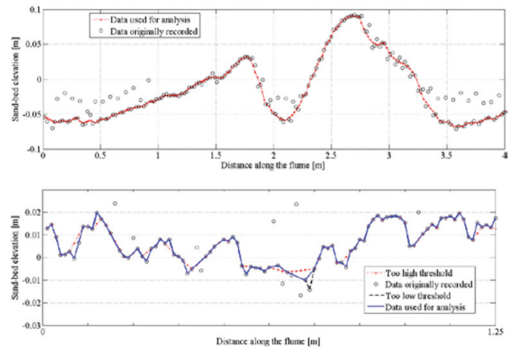

Figure 9. Post-processing comparison of dune bedforms (top) and ripple bedforms (bottom).

5 DISCUSSION

As pointed out above, there are limited publications on data requirements for bedform analysis. In general, laboratories have limited resources and research is undertaken with what is available. The small range of datapoints recorded to describe bed profiles in the past, in the vicinity of 2–3 digits for bed profiles, made manual post-processing often easier and more time efficient than developing an automatic procedures to de-noise data. With the advent of new measurement technologies and better computer resources, millions of data points can be recorded and analyzed, representing one bed profile. Although the quantity of information used to describe one bed profile is increased, robust quality assurance procedures need to be in place to guarantee that the recorded data is suitable for analysis.

Still valid is Nordin's (1971) recommendation on the data needs for spectral analysis. He identified the following data suitability parameters:

- the record length
- the sampling rate
- the maximum lag

Spectral analysis can obtain the smallest bedform length as twice the sampling rate, and the largest bedform length as twice the product of the sampling rate and the maximum lag of the record. Thus, Nordin (1971) suggested that the record length should be no less than 10 times the product of the sampling rate and the maximum lag of the record. Following on, for an individual bed feature, here a dune, Nordin (1971) recommended to have 20–30 data points per average dune length, with the overall record length being 10–20 times that for the average dune length. Those numbers are provided for regular dune features; there are exemptions for superposed bed features, such as ripples on dunes, or dunes on bars.

Compare those with Friedrich's (2010) suggestion, who not only studied dune beds but also rippled beds, where the average ripple height for some runs was 20-mm, with an average ripple length of 0.2-m for equilibrium bedforms (Fig. 10), and even less during the development stage.

Friedrich's (2010) rippled bed spatial dataset was recorded at a sampling rate of 12.5-mm, resulting in 16 or less data points per ripple length, depending on development stage. This is substantially less than the 20–30 data points per bedform recommended by Nordin (1971). As Figure 10 shows, the ripples surface features appear less smooth than one would observe them when standing next to the flume, and thus the ripple data have only limited suitability for detailed analysis. For the continuous approach, smaller roughness scales will not be able to be detected, and for the discrete approach any determination associated with height and length features will have a substantial error rate associated with. If, in addition, the original signal is heavily contaminated (such as recording of suspended particles) or contains empty signals (such as malfunctioning sensors or empty grid values) sufficiently more than 20 signals are required to describe a bedform accurately.

Nordin (1971) did not discuss the requirements for accuracies in elevation measurements. Again for ripples beds, Friedrich (2010) pointed out that the used recording accuracy of ±1.00-mm for the experiments resulted in possible inaccuracies of 5% for individual signals, based on an average ripple height of 20-mm, or up to 10% for neighboring signals.

In turbulence studies, it is now good practice to follow common methods of velocimeter data post-processing, datasets which are in essence very similar to modern high-resolution bed-surface datasets. Various research studies concentrated on flow velocity data evaluation (Biron et al., 1995, Biron et al., 1998, McLelland and Nicholas, 2000, Nikora and Goring, 1998, Voulgaris and Trowbridge, 1998, Hurther and Lemmin, 2001, Blanckaert and Lemmin, 2006, Meile et al., 2008). Chanson et al. (2008) provided a good overview of

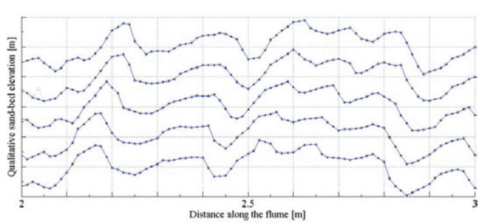

Figure 10. Recording developing bedform with 16 data points per bedform.

the post-processing procedures which should take place for velocimeter datasets:

- Velocity signal check. This involves the removal of all communication errors, low signal-to-noise ratio data (<5 dB) and low correlation samples (<60%–70%).
- For field studies, event detection and removal. Use of a low-pass/high-pass filter threshold, to remove probe motion, navigation and other events which might contribute to more noisy data.
- Despiking. This involves detection and removal of small disturbance, with the phase-space threshold technique (Goring and Nikora, 2002), which is commonly accepted for low-accelerating flows.

For velocimeter datasets, the frequency of the measurement equipment dictates the sampling rate. More recently, velocimeters with sampling rates up to 200 Hz became available. Such a high sampling rate increases the likelihood of noise. Although general velocimeter post-processing procedures, as outlined above, seem to be more widely accepted and used, the information of how many data points are 'lost' and subsequently interpolated in each step is not necessarily provided by the researchers applying the methodologies. Table 3 in Chanson et al. (2008) shows a summary of post-processing effects on the overall dataset.

However, clear guidelines of how to achieve a natural representation of bedform recordings and use of post-processing techniques are not published.

6 CONCLUSION

The paper is intended to highlight and share some of the observations in regards to the need to obtain modern high-resolution bed surface data, as well as the new post-processing challenges those datasets post. Major comprehensive datasets in the past, which were mainly used to obtain discrete geometric characteristics of bedforms, often relied on various means of visual observations (eye, drawing, photo and more recently video). Datasets obtained by mechanical means, might have ~1000 data points per experiment, often less. In comparison, the authors' approach easily facilitates collection of multitudes of 1-million data points per profile, depending on the number of mechanical sensors used.

It is shown that a stream-lined and accepted process of transferring the raw data to post-processed data is required. Only then can such post-processed data be used for analysis, be it the discrete approach or the continuous approach. Most importantly, criteria need to be set in place to ensure post-processing transformations keep the character of the bed-surface features intact and do not introduce additional noise.

A similar widely accepted post-processing methodology is in place for velocimeter datasets, which when comparing data quantity, can be similar to the data quantities encountered in modern bed profile datasets. Although there exists a lack of transparency in the quantity of data points detected and excluded/replaced during velocimeter post-processing. Especially when applying the continuous approach methodology, which has its existence in turbulence research, substantial or incorrect replacement of data points can lead to substantial errors and misinterpretation of final results.

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