The influence of geometric definitions on dune characteristics

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ABSTRACT: Dune height and length are two widely used measures to characterize a bedform, but their geometric definitions are not consistent throughout the literature. In this sensitivity study, we investigate how different definitions can influence the dune dimensions of three benchmarking data sets. In particular, we quantify relative differences and interpret them against the background of dune inclination and asymmetry. Dividing the results into subsets of bathymetries and dune sizes allows us to attribute the causes for significant differences before discussing practical implications and recommendations.

1 BACKGROUND

Subaqueous bedforms have been the subject of scientific investigations for more than a century (Cornish, 1901). These geomorphological features, also known as sand waves, dunes or (mega-)ripples, can be observed in diverse flow environments including rivers (Cisneros et al., 2020; Zomer et al., 2021), tidal inlet channels (Lefebvre et al., 2022; Scheiber et al., 2021) and continental margins (Durán et al., 2020; Miramontes et al., 2020). With regard to their geometric extents, individual bedforms can reach tens of metres in height and hundreds of metres in length (Franzetti et al., 2013). When measuring these critical dune characteristics, however, various geometric definitions are used in scientific literature (cf. Fig. 1). For instance, dune length is measured as the horizontal distance (L_1)

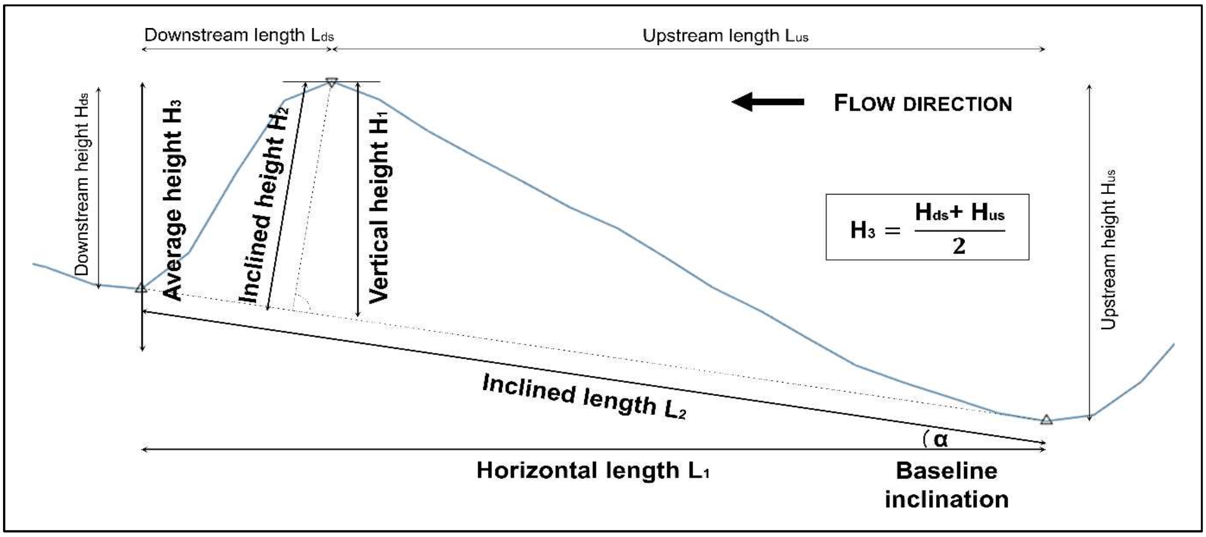

Figure 1. Common geometric definitions for calculating height and length of a dune, which is, in our case, defined by two troughs. If these are (nearly) on the same level, horizontal and inclined lengths can be assumed equal. The same applies for height, which can also be calculated from average up- and downstream heights.

between two troughs (or two crests) or as the inclined distance (L_2). In a similar way, dune height can either be calculated as the vertical height (H_1) or inclined height (H_2). A third option with regard to the calculation of height is averaging vertical distances between the crest and up- and downstream troughs (H_3).

Applying these different definitions will result in small deviations, if the troughs are roughly on the same level, but larger deviations can be expected over inclined bedforms. For instance, this can be the case at so-called compound dunes, where small secondary dunes are superimposed on the slopes of larger primary dunes. This poses the risk of inaccuracies, especially when dune characteristics are used as a proxy for more complex processes. In this study, we quantify the sensitivity of existing height and length definitions by systematically assessing three benchmarking data sets. On this basis, we discuss the available options and try to give a final recommendation.

2 METHODOLOGY

To allow for the full range of bedform types, we selected benchmarking data sets from three different flow environments: a flume, a river and a tidal inlet channel. In-depth descriptions of these bathymetries can be found at Bradley and Venditti (2019), Parsons et al. (2005) and Lefebvre et al. (2022), respectively. To avoid any bias from the natural constraints, all data sets were limited to 100 transects of 450 m length each. As an example, Figure 2 shows one of these transects from the Weser tidal inlet below the corresponding surface plot. After identifying prevailing bedforms with the semi-automated algorithm presented in Scheiber et al. (2021), we calculate corresponding dune dimensions based on the aforementioned definitions. The resulting arrays, three for dune heights H_1 / H_2 / H_3 and two for dune lengths L_1 / L_2, are then compared with each other.

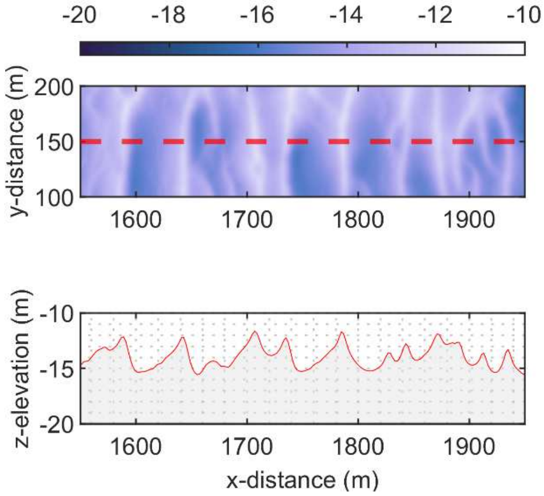

Figure 2. Bed elevation map (top) and exemplary transect (bottom) highlighting the tidally-constrained bedforms in the Weser inlet channel.

A helpful indicator for contrasting two results arrays is the relative difference d_r, which relates absolute differences to arithmetic mean values. For our specific case, this could read as follows:

$$d_r = \frac{H_1 - H_3}{\left(\frac{H_1 + H_3}{2}\right)} \qquad (1)$$

where H_1 is the vertical and H_3 is the average dune height. This relative difference can be calculated for all identified bedforms. In a second step, its frequency of occurrence can be assessed and displayed in histograms. This gives us valuable information about how often and where specific differences can be expected. The repercussions of these differences are also present in the statistical parameters that describe the frequency of results, most prominently arithmetic mean and percentile values, which are often used to characterize the physical properties of a dune field. After assessing the complete results data set in the first instance, we repeated the described analyses for the subsets of (three) individual bathymetries and (five) dune size classes according to Ashley (1990) to better understand the reasons for particularly high sensitivities.

3 RESULTS AND DISCUSSION

Table 1 summarizes the arithmetic mean values for the most relevant parameters in this sensitivity study. The first line contains the results for all 21,939 assessed bedforms and already points at a crucial finding: the differences between vertical and inclined dune heights (H_1 vs. H_2) are remarkably small. The same applies for horizontal and inclined lengths (L_1 vs. L_2), which can also be seen in the distribution of their relative differences in Figure 3 below.

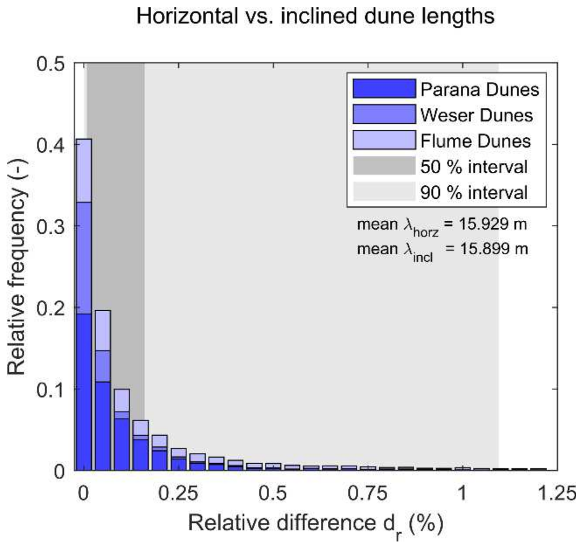

Figure 3. Relative frequency of occurrence for the relative differences between horizontal and inclined dune lengths. Blue shades relate to the three bathymetries and grey shades represent the 50 % and 90 % intervals, respectively.

In this illustration, dark and light grey patches illustrate the 50 % and 90 % intervals, respectively. The depicted intervals imply that 19 out of 20 assessed dunes show length deviations of less than 1.1 %. Related to the presented mean lengths, this translates into an absolute difference of 17.5 cm. However, the mean length itself only deviates by 3.0 cm. This similarity of results is corroborated by data about the dune baseline: an average inclination of $\alpha = 2.544°$ corresponds to a ratio between L_1 and L_2 of $\cos \alpha = 0.999$, which makes these approaches nearly equal.

Although this trend holds true for dune heights H_1 and H_2 as well, deviations of the average height H_3 are significantly larger. For instance, mean values for H_1 and H_2 are almost identical ($\Delta H \leq 0.3$ cm) throughout all bathymetric subsets, whereas H_3 mean values are between 9.0 and 32.7 cm higher than H_1 and H_2. This points at a systematic divergence, which can also be traced in the distribution of relative differences in Figure 4. One third of all dunes yields negligible differences of ± 5 % or less. However, the remainder of the frequency distribution shows a pronounced left tail. Overall, the average relative difference for the complete data set is -26.8 % with particularly high values in the subset of large dunes. Even though the average baseline angle reaches its maximum in this group, relative differences do not scale with dune inclination alone as the comparison with bathymetric subsets shows:

Table 1: Arithmetic mean values for three dune height (H) and two dune length (L) definitions. These values are complemented by the corresponding sampling sizes (N), information about the baseline inclination (α and $\cos \alpha$), the relative difference (d_r) between vertical and average dune heights as well as the ratio between left and right dune slopes (L_l/L_r) as a proxy for dune asymmetry. The total data set was further differentiated into subsets depending on bathymetry and dune size classes according to Ashley (1990), respectively.

Data Set	N (-)	H_1 (m)	H_2 (m)	H_3 (m)	L_1 (m)	L_2 (m)	α (deg)	$\cos \alpha$ (-)	d_r (%)	L_l/L_r (-)
Total	21,939	0.481	0.480	0.648	15.899	15.929	2.544	0.999	-26.806	2.916
Paraná	10,926	0.264	0.264	0.354	9.438	9.451	2.251	0.999	-25.894	2.800
Weser	4436	0.779	0.779	0.903	33.909	33.920	1.117	1.000	-16.885	2.429
Flume	6577	0.641	0.638	0.965	14.484	14.558	3.993	0.995	-35.014	3.435
Small	7320	0.130	0.129	0.146	3.253	3.258	2.261	0.999	-10.839	1.460
Medium	6223	0.202	0.201	0.272	6.660	6.675	2.389	0.999	-25.479	2.259
Large	8263	0.977	0.975	1.353	32.491	32.557	2.946	0.999	-42.375	4.722
Very large	133	2.097	2.097	2.098	113.325	113.329	0.375	1.000	-0.501	1.593

the flume data contains dunes that are even more inclined, but relative differences are not as extreme as in the set of large dunes. This is because vertical and average heights are only identical in case of symmetrical dunes. Although such cases exist, bedforms under natural conditions are frequently asymmetric. In this study, the most symmetric bedforms are those from the tidally-constrained Weser bathymetry, which consequently coincide with minimal relative differences (cf. Tab. 1).

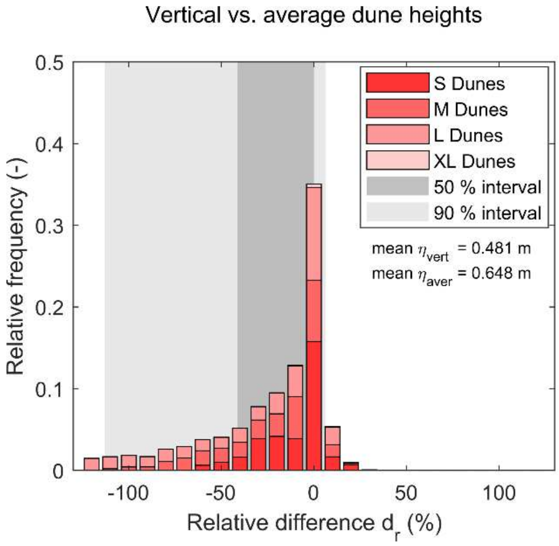

Figure 4. Relative frequency of occurrence for the relative differences between vertical and average dune heights. Red colours correspond with dune sizes according to Ashley (1990).

With regard to practical implications, we can draw two major conclusions from these findings: first, the inclination of a baseline can be neglected when calculating dune characteristics ($L_1 \approx L_2$ and $H_1 \approx H_2$), independent of the prevailing flow conditions or dune sizes. Secondly, using average dune heights yields significantly different results for the case of asymmetric dunes ($H_3 \neq H_1$). But nevertheless, both measures can be justified. H_1 and H_2, one the one hand, define dune height phenomenologically as the extent that a bedform crest can rise from the surrounding sediment. On the other hand, H_3 is used to describe dune height in terms of a vertical obstacle or roughness element that impedes horizontal flow. It is therefore not helpful to discard or propagate one definition in general. Rather than that, a suitable height definition should be chosen with care and applied consistently throughout connected analyses. The presented results can be seen as a sound basis for such decisions.

4 CONCLUSIONS

Dune height and length are widely applied to describe bedforms, but various definitions co-exist in academic literature. The presented sensitivity analysis scrutinizes, how the choice for a specific definition can impact results. According to our systematic analysis of three benchmarking bathymetries, the inclination of natural dunes is typically small enough to regard horizontal and direct trough-to-trough distances as equal. The same applies for vertical and orthogonal dune heights. However, the average dune height can yield significantly larger values than the aforementioned definitions with relative differences occasionally exceeding -100 %. In the present case, the average relative difference is -26.8 % at a sampling size of 21,939 bedforms in total. Although this finding illustrates the importance of a suitable height definition, it still leaves readers with an independent choice: while both vertical and orthogonal dune height reflect the physical constraints of dune growth, average dune height can be used to describe flow resistance. Hopefully, the findings of this study can support other bedform enthusiasts in choosing the most suitable geometric definitions for their research.

5 ACKNOWLEDGMENT

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