Ripples and dunes: do flumes tell the whole story?

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ABSTRACT: Field observations have revealed the existence of small ripples (L=8 cm) in coarse sand (D=0.87 mm). This contradicts the conventional perception that ripples, defined as L <0.6 m, do not occur in sediments coarser than about 0.7 mm. As the currently accepted dimensional differentiation between ripples and dunes has essentially been based on flume observations, the contradictory evidence suggests that flumes, i.e. very shallow flows, suppress or inhibit the development of the smallest ripple-sized bedforms across all grain sizes. A plausible explanation for this could be that, in depth-limited flows, the turbulence generated by friction along the bed is confined to the small flow cross-sections and thereby prevents the formation of very small ripples.

1 INTRODUCTION

Phase diagrams of flow-transverse bedforms observed in flumes and shallow natural flows commonly distinguish between ripples and dunes (Figure 1). The main morphological criterion for this distinction is that ripples have spacings <0.6 m (Allen, 1984; Sumer and Bakioglu, 1984), whereas dunes have spacings larger than 0.6 m (Costello and Southard, 1981; Allen, 1984; Sumer and Bakioglu, 1984; Ashley, 1990). Earlier, Yalin (1977) had, in addition, defined dunes as bed forms that interacted with the water surface, whereas ripples did not. He did not, however, provide any boun-dary conditions for which this definition was supposed to be valid. There is now overwhelming evidence that this criterion does not apply in deep flows (e.g. Flemming and Bartholomä, 2012, and citations therein). At the same time, Yalin (1977) suggested that, at initiation, flow-transverse bed forms had spacings of about 1000 grain diameters (L_{min} = 1000D), a concept that fitted the implied dimensional differentiation between ripples and dunes.

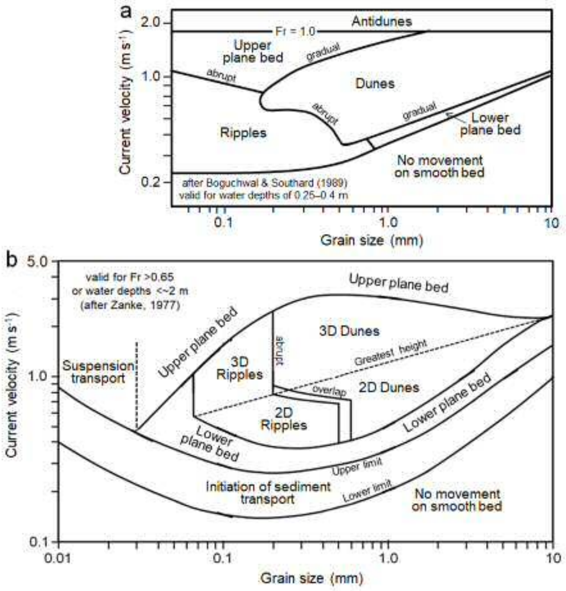

Figure 1. a) Bedform phase diagram of North American researchers (based on Boguchwal and Southard, 1989). b) Bedform phase diagram of German hydraulic engineers (based on Zanke, 1976). Note identical vertical and horizontal scales.

Finally, also on the basis of flume experiments, Simons and Richardson (1966), Costello and Southard (1981), Allen (1984), Sumer and Bakiogly (1984), Chiew (1991), van den Berg and van Gelder (1993) and Kleinhans (2002) concluded that, at grain sizes larger than about 0.65–0.7 mm, ripples no longer formed and the initial bedforms were dunes (L>0.6 m). Good reviews of these definitions and delimitations can be found in Carling (1999) and Best (2005).

In this context, it is instructive to compare standard bedform phase diagrams constructed by different researchers, here from Boguchwal and Southard (1989), USA, and Zanke (1976), Germany, in each case on the basis of their respective flume data (Figure 1a, b). While the diagrams have much in common, they also show significant deviations from each other, which seem to reflect different perceptions in data inter-pretation and presentation.

Thus, in diagram a, the initiation of movement is based on Shields (1936), while that in diagram b is based on Hjulström (1935). Furthermore, lower plane bed transport is restricted to grain sizes larger than about 0.7 mm in diagram a, whereas diagram b shows lower plane bed transport at all grain sizes. Furthermore, considering the shallow water, the pinching out of the dune stability field towards larger grain sizes in diagram b is a clearly more realistic representation of the observations than in diagram a, where the stability field to the right remains open-ended. The larger vertical phase scaling of diagram b reflects its validity for water depths up to 2 m, whereas the validity of diagram a is restricted to water depths up to 0.4 m. A particularly interesting aspect of diagram b is the distinction between 2D and 3D forms, the diagonal broken line indicating the maximum bedform height reached by ripples and dunes in those experiments.

In the light of the above, the main purpose of this investigation is to present new observational data that questions the validity of the conventional distinction between ripples and dunes, and to discuss the implications thereof.

2 METHODS

In this article the information presented in standard phase diagrams of flow-transverse bedforms observed in flumes and shallow flows is analysed in the light of recently published and new observational data concerning initial bedform spacing as a function of grain size.

3 RESULTS

In the course of a field trip to the Valdez Peninsula (Argentina) in 2016, the author spotted ripple formations in evidently coarse sand on a channel bar at low tide (Figure 2). The spacing of the bed forms ranged from 30 cm to a smallest size of 8–9 cm. A subsequent sieve analysis produced a median grain size of D_{50} = 0.87 mm, which would correspond to an approximate minimum spacing (L_{min}) of 100D.

Figure 2. Ripples in coarse sand (D_{50} = 0.87 mm) on a tidal channel bar (southwestern San José Gulf, Valdez Peninsula, Argentina). Note that the smallest examples have spacings of 8–9 cm.

According to the morphological criteria for the distinction between ripples and dunes outlined above, and consistent with the bed phase diagrams of both Boguchwal and Southard (1989) and Zanke (1977), ripples should not occur at all in such coarse sediment, let alone such small ones. As both the flume and the field evidence must be accepted as being true representations of the respective observations, something must be amiss with the flume data. The only explanation would seem to be that in flumes, and probably also very shallow natural flows in general, the development of initial ripple-size bedforms is, for some reason, supressed or inhibited. This not only applies to grain sizes larger than 0.7 mm but also to finer sediment, as can be deduced from Figure 3 (cf. data points of Baas, 1994, 1999).

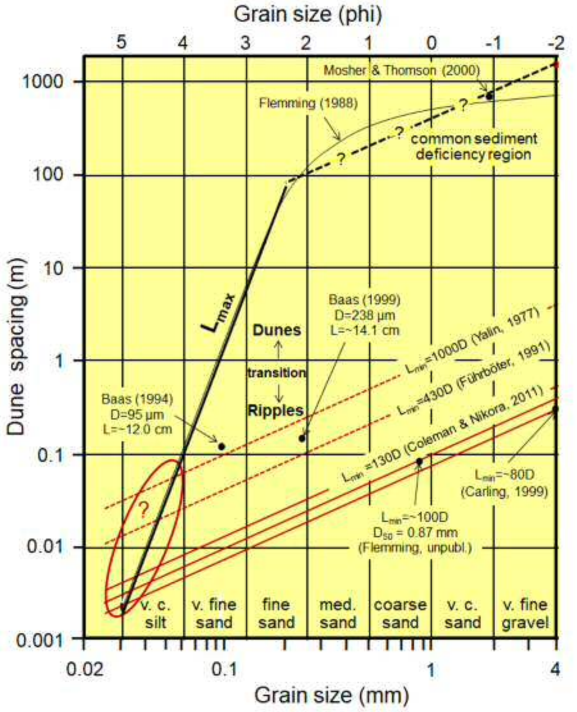

Figure 3. Initial and largest spacings of ripples and dunes as a function of grain size. Initial spacings (L_{min}) as defined by grain diameters (D) after various researchers; largest spacings (L_{max}) as observed in nature (modified after Flemming, 1988).

The above discrepancy has in recent years also been fuelled by the suggestion that minimum spacings of flow-transverse bedforms can be expressed in terms of grain diameters (Figure 3). The L_{min} = 1000D relation proposed by Yalin (1977) has already been mentioned. Führböter (1991) suggested a relation of L_{min} = 450D. More recently, Coleman and Nikora (2011) proposed the relation of L_{min} = 130D, while L_{min} = 80D for a mean grain size of 4 mm can be inferred from data published in Carling (1999). A point of interest here is the progressive reduction in the grain scaling over past decades. The narrow band defined by the relations of Coleman and Nikora (2011), Carling (1999) and Flemming (this article) can be viewed as the initiation zone within which initial bedforms appear to evolve (Figure 3). It should also be noted that the 1000D and 450D proposals are in conflict with the size of ripples known to occur in very coarse silt. Furthermore, the data compiled in Figure 3 contradict the view that dunes do not scale with grain size (Ashley, 1990), this contention having been exclusively based on observations made in depth-limited flows.

The trend lines tracing the largest bed forms (L_{max}) in Figure 3 are based on multiples of the 100D criterion. If, instead, the 130D or 80D criteria were used, the corresponding L_{max} trend lines would lie slightly above or below those trend lines. For comparison, the L_{max} trend line of Flemming (1988), which was based on rather scarce observational data, is also shown (thin grey line).

4 DISCUSSION

A first point to be discussed concerns the question as to why very small bedforms apparently do not develop in very shallow flows. A plausible explanation for this could be the interference of turbulence generated by friction at the bed. In shallow or depth-limited flows the vertical expansion of the frictional boundary layer terminates at the water surface. In deep, depth-independent flows, by contrast, the thickness of the boundary layer can be approximated by the relation $\delta_{bl} = 30U_{mff}$, where δ_{bl} is the thickness of the boundary layer in metres and U_{mff} is the mean free flow velocity above the boundary layer in m/s (Flemming, unpublished). Thus, already at a critical velocity of 0.25 m / s, the boundary layer would expand to a height of 7.5 m above the bed if given sufficient water depth. In deep flows, the turbulence generated at the bed can thus spread across the entire boundary layer (in the above case across 7.5 m). In depth-limited flows such as flumes (e.g. 0.4

m in the case of Figure 1a), the turbulence is concentrated near the bed, which may result in the suppression or inhibition of the development of very small bedforms.

A second point to discuss is whether the conventional distinction between ripples and dunes can be upheld in the light of the grain scaling concept of initial bedform spacing (L_{min}) outlined above and illustrated in Figure 3. In fact, Figure 3 suggests that ripples (as currently defined) occur in grain sizes up to at least 8 mm, although this does not appear to be reproduced in flume experiments. A consequence of this is that the assumed genetic difference between ripples and dunes turns out to be entirely artificial, being simply due to the incomplete nature of data generated in severely depth-limited flows. An interesting point to be made here is that the small ripples in Figure 2 were preserved at low tide, i.e. in the course of decelerating flow. This may explain the formation and preservation of the smallest forms.

A final point of discussion is the question of how large flow-transverse bedforms can become (L_{max}) under ideal conditions, i.e. where flow velocities and water depths are large enough. The field evidence clearly shows that the growth of ripples and dunes is ultimately limited by grain size. This is illustrated in Figure 3 by plotting L_{max} against grain size based on multiples of 100D. The steeper trend line represents grain sizes up to about 0.2 mm and is well constrained by observational data (cf. Flemming and Bartholomä, 2012). For coarser grain sizes the trend line follows a substantially lower gradient, running almost parallel to the L_{min} trend lines. Although both trends are to variable extent supported by field data, the data base for the lower-gradient trend line is much poorer because of the increasing sediment deficiency with increasing grain size and dune size. Nevertheless, the single data point from Mosher and Thomson (2000) shows good agreement with this trend.

Flemming (2000a) suggested that dune growth is terminated when the flow velocity above the crest reached the point where part of the bedload began to bypass the crest in suspension. It was assumed that this condition was fulfilled when the settling velocity of the average grain size (w_s) was equal to the shear velocity (u_*). According to Graf and Acaroglu (1966), approximately 40% of the bed material would be in suspension when this condition is reached. The choice of this criterion by Flemming (2000b) was thought to be justified by the fact that, when two dunes of similar size amalgamate, the geometric relationships dictate that about 40% of the larger dune body is initially missing. However, without sediment bypassing, the missing sediment is gradually regained by lowering of the base level through trough scouring in the course of amalgamation (Flemming, 2000b).

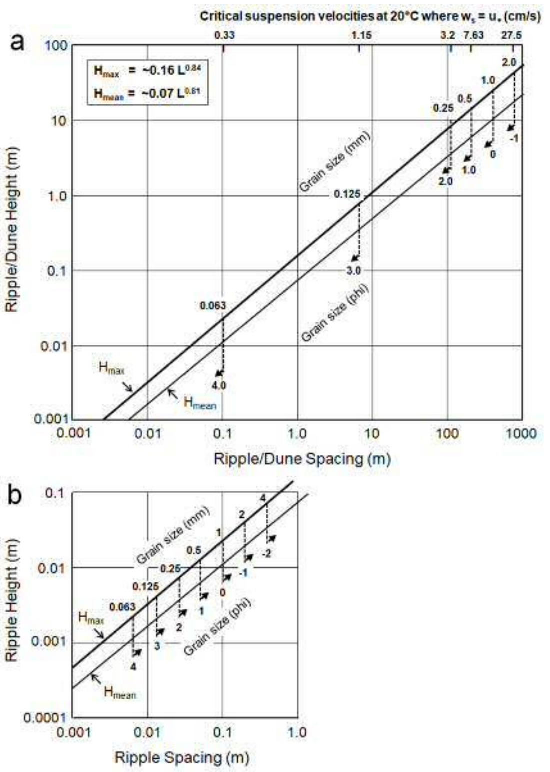

Figure 4. Size ranges (H vs L) of ripples/dunes as a function of selected mean grain sizes; **a** maximum dimensions; **b** initial dimensions. Note that for all grain sizes shown here the initial forms are ripples. Also shown are the corresponding suspension velocities for $w_s = u_*$ valid at a water temperature of 20°C.

To illustrate the dependence of ripple and dune dimensions on grain size, the L_{max} and L_{min} values generated by the 100D criterion were plotted into the height versus spacing diagram of Flemming (1988) for grain sizes corresponding to full phi steps (Figure 4). To avoid confusion between the two, the L_{max} and L_{min} limits were plotted separately in Figure 4a, b, respectively. From the diagrams it can be seen that both the size range and the maximum size of dunes increase with increasing grain size. This is supported by numerous observations in nature.

5 CONCLUSIONS

The main conclusions of this investigation are:

- Flumes evidently do not tell the whole story.
- Flumes (and probably shallow flows in general) appear to suppress the initial development of ripple-size bedforms, especially in sediments coarser than about 0.6 mm.
- A possible reason could be the high concentration of turbulence near the bed in shallow flows.
- The intitial spacing of flow-transverse bed forms appears to follow the rule of L_{min} = 100–130D, which appears to be valid for all grain sizes.
- Carefully designed studies are required to gain a better understanding and a more definitive explanation of this phenomenon.
- A promising approach could be the investigation of bedform evolution in decelerating flows, i.e. working backwards from higher to lower velocity regimes.

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