The role of grain size, water depth and flow velocity as scaling factors controlling the size of subaqueous dunes

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Abstract

The dimensional parameters (height, spacing) of subaqueous flow-transverse bedforms (ripples and dunes) define a highly correlated exponential relationship which has universal character. However, site-specific data sets rarely conform to this global trend. While such disagreements do not mitigate against the global trend, they do require explanations on the basis of the locally prevailing conditions. Amongst such local factors are changing flow depths, rapidly changing flow velocities, inadequate sediment budgets, and storm wave action. In addition, measuring errors can distort the scatter plots. Evidence is provided which precludes water depth as a primary control factor. It will simply terminate further dune growth once flow acceleration above the dune crest reaches a grain-size dependent critical suspension velocity. In depth-limiting flows dune height (or spacing) and water depth are therefore inherently correlated. In deep water, by contrast, dune growth is not limited by water depth. Dunes will continue to grow in response to increases in mean flow velocity until the critical suspension threshold for a given grain size is reached. Since critical suspension thresholds increase with increasing grain size, maximum dune size must increase with increasing grain size. For example, for a mean grain size of D = 0.063 mm $H_{max} \approx 0.03$ m and $L \approx 0.14$ m, for D = 0.125 mm $H_{max} \approx 0.8$ m and $L \approx 7$ m, for D = 0.25 mm $H_{max} \approx 9$ m and $L \approx 125$ m, or D = 1 mm, $H_{max} \approx 35$ m and $L \approx 600$ m. From this follows that, in order to achieve maximum size for a given grain size, the water depth has to be correspondingly deep and the flow velocity correspondingly high, bedform growth proceeding in steps by which smaller dunes amalgamate to form larger dunes. Taken together, the critical factors involved in the development and growth of flow-transverse bedforms would appear to be best accommodated by a kinematic wave theory.

Introduction

Since the first systematic studies of a subaqueous dune fields (e.g. Exner 1925; Lane and Eden, 1940), a large number of studies have been carried out in both natural flows and experimental flume systems (e.g. Ashley, 1990; Southard, 1991). Many of these are case studies either documenting the results of carefully controlled experiments, or recording site-specific situations such as the flow conditions and local bed parameters such as dune height, dune spacing, and grain size. In some cases the results are compared with those from other regions, but rarely were explanations provided for any observed differences, the recent study by Wewetzer and Duck (1999) being a good example. Only a few studies have analyzed pooled data sets from different environments and geographic locations with the aim of distinguishing local characteristics from more universal relationships. Amongst these are the studies of Allen (1968a, 1968b, 1982), Jackson (1976), Flemming (1978, 1988), Rubin and McCulloch (1980), and Carling (1996, 1999).

In this paper a fresh look is taken at some important factors involved in bedform generation and control. Particular attention is given to height/spacing relationships, the influence of water depth, the role of grain size, and the effect of flow velocity. By pooling and/or comparing data sets from different regions, an attempt is made to distinguish local effects from relationships evidently having a more universal character. The overriding aim is to provide some basic insights which may contribute to the formulation of a general bedform theory.

1. Dune height versus spacing

The most comprehensive compilation of dune size data was presented by Flemming (1988). It incorporates published data from flume studies and a variety of natural environments in different parts of the world, including tidal current dominated shelf seas, ocean current dominated continental shelves, marginal seas experiencing episodic inflow events, large and small estuaries, and rivers. Of the 1491 height/spacing measures, 550 were derived from the southeast African continental shelf (Flemming, 1978, 1981, 1988), the remaining 941 having been extracted from the literature. The data are highly correlated (r = 0.98), being described by the positive exponential relationship **$H_{mean} = 0.0677\ L^{0.8098}$** corresponding to the linear log/log regression illustrated in Fig. 1A. The scatter plot also reveals a sharply defined upper limit that can be approximated by the linear log/log relationship **$H_{max} = 0.16\ L^{0.84}$**. It suggests the existence of an upper height limit for any given spacing, a relationship that can be described by a maximum dune steepness index (L/H) in each case. Since the spacing increases more rapidly than height, the dune steepness index does not remain constant, but increases the larger a bedform grows. Of the two trend lines, the one describing the mean H/L relationship has a slightly lower slope than that describing the maximum H/L relationship. This is due to the fact that the larger a bedform grows, the higher the probability is that insufficient sediment is available for the construction of the complete dune body. The result is an incomplete or sediment starved dune, characterized by a substantially lower height than would be predicted by the equation (cf. Flemming, 1981). Clearly, such data would distort the scatter plot.

The diagram in Fig. 1A integrates a large global data set which ranges from very small to very large flow-transverse bedforms (H ≈ 0.001-20 m, L ≈ 0.01-1000 m). As a consequence, the relationships outlined above can claim to have universal character. The specific trends described by the two equations, however, are nevertheless circumstantial in that they reflect the interrelationships of this particular data set. Additional data would most probably produce slightly different numerals and exponents, although the general trend would not be expected to change dramatically. This feature means that one should not expect site-specific data sets to accurately reproduce the global trend, especially if they cover limited size ranges only. A selection of regression lines from different environments is illustrated in Fig 1B. It clearly demonstrates that the individual data sets have quite different mean H/L relationships, each one departing substantially from the global mean trend. In comparing local trends with the global trend, many authors simply note the agreements or disagreements without further discussion, others question the validity of the global trend because their data does not appear to fit the global relationship (e.g., Wewetzer and Duck, 1999). In view of the arguments presented above, any departure from the global trend requires explanation as it reveals important process-response features characterizing the local environment. Thus, four repeated surveys of a dune sequence occurring along a 100 km long stretch of the southeast African continental shelf produced four different height/spacing trends, only one approximating the mean global trend (Flemming, unpubl.). In this case, changing flow conditions and varying sediment supply were identified as the main causes for the departures. Similarly, Flemming and Davis (1992) have demonstrated that the temporal variability in height/spacing trends of subtidal dunes was a process-response feature resulting from changes in the flow associated with the spring-neap tidal cycle. The mean global trend thus serves as a useful reference against which local trends can be compared.

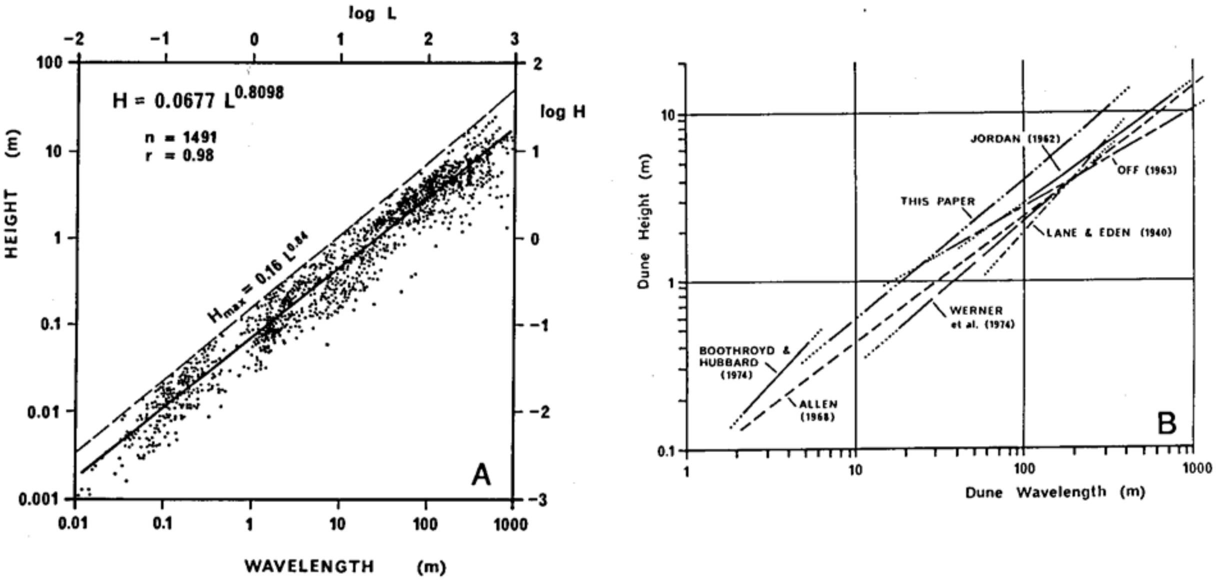

Fig. 1. Dune height versus dune spacing. A: Scatter diagram incorporating data from flumes and many different natural environments (after Flemming 1988). B: Diagram illustrating mean trends of a selection of individual data sets (after Flemming 1978).

Another feature of the scatter diagram which requires attention is the apparent data gap from L ≈ 0.6-1.0 m. Some researchers have associated this gap with the dimensional "jump" from ripples (L < 0.6 m) to dunes (L > 1.0 m) observed in flume studies (cf. Ashley, 1990; Southard, 1991). According to this interpretation the gap is considered to be real, reflecting the non-existence of flow-transverse bedforms in this size interval. New data, however, proves that we are dealing here with an observational gap (Flemming, unpubl.). Interestingly, the data plotting in the gap stem from flow-transverse bedforms generated in very coarse sand and fine gravel. On the one hand, this explains the general dearth of data in this size interval, observations and measurements in such coarse sediments either lacking completely or not having been reported in the literature. On the other hand, the fact that only bedforms in coarse sediments have H/L relationships in this size interval reveals an important aspect of bedform growth. There is now convincing evidence that bedforms grow in steps (or jumps) by amalgamation (Flemming, this volume). Since initial bedform size is a function of grain size, ripples and dunes generated in different sediments will grow with different step sequences in the course of amalgamation. For example, a ripple in fine sand with an initial spacing of 7 cm would grow in a step sequence of 14 cm, 28 cm, 56 cm, 112 cm, etc. Note the gap from 56-112 cm. A coarser sediment with an initial ripple spacing of say 20 cm would grow in the step sequence of 40 cm, 80 cm, 160 cm, etc. In this case one of the steps falls into the apparent gap. Since the scatter plot in Fig. 1A incorporates a wide variety of grain sizes, the stepped pattern associated with a particular grain size is obscured.

The stepwise growth appears to be better preserved in larger bedforms because adjustments to changes in the flow take a relatively long time, large quantities of sediment having to be moved. In small bedforms, by contrast, the response to flow perturbations is rapid because very little sediment has to be moved. As a result, the growth pattern may not be as evident as in the case of larger bedforms. The growth model outlined above is consistent with observations and suggests that the supposed hydraulic difference between ripples and dunes is artificial, the two actually belonging to the same family of flow-transverse bedforms.

2. Water depth as a limiting factor

It is commonly argued that a major factor distinguishing ripples from dunes is the fact that the latter interact with the water surface, i.e. that dune dimensions are scaled with the water depth, whereas ripples are independent of water depth (e.g. Yalin, 1992). Such dependencies were first documented by Allen (1963, 1968a) for dune height and by Jackson (1976) for dune spacing. Other studies, however, have produced contradictory evidence which clearly demonstrates that this relationship does not apply in general (cf. Fig. 2A and 2B; also see Wewetzer and Duck, 1999). Accepting the validity of the published data, it means that in some cases dunes scale with water depth, in othes they don't. How can this be explained? A closer look at Figs. 2A and 2B reveals that in all cases where the data is contradictory we are dealing with relatively deep flows (10-100 m). Furthermore, the largest dunes of each data set actually fall into the range where a dependence of water depth has been documented.

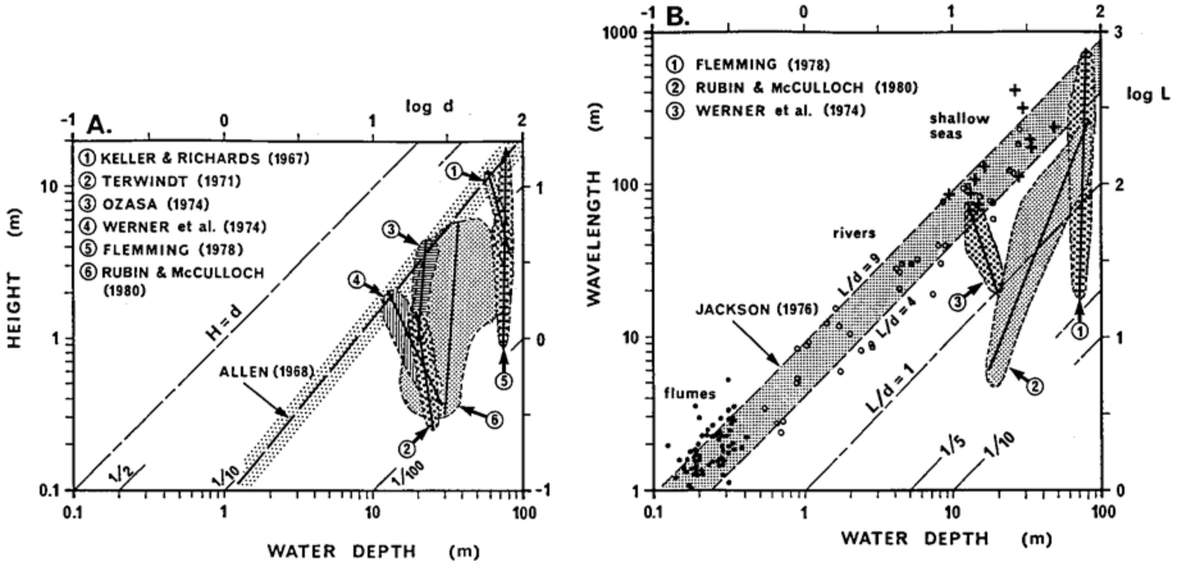

Fig. 2. The relationship between dune dimensions and water depth on the basis of published data. A: Dune height versus water depth. B: Dune spacing (wavelength) versus water depth.

The available data clearly demonstrate that the contention that dunes interact and hence are scaled with water depth as a matter of principle must be rejected. Water depth is therefore not a primary control factor in defining dune size. It will simply terminate further dune growth once flow acceleration above the dune crests reaches a grain-size dependent critical suspension velocity. In depth-limiting flows dune height (or spacing) and water depth are therefore inherently linked. However, the resulting scaling factor is clearly also a function of the grain size. Coarser sediments should thus have lower height/depth or larger spacing/depth ratios than finer sediments. The rule of thumb that the maximum bedform height (H) is reached at water depths (d) of d ≈ 6H and spacing (L) at water depths of L ≈ 6d (cf. Yalin, 1992) must therefore be treated with some reservation because it is not the water depth *per se* which scales the bedform sizes, but rather the grain-size dependent critical suspension velocity. The effective depth differences are probably small and the above ratios are in practice therefore a useful, but nevertheless crude first-order approximation. Indeed, both the height/depth regression of Allen (1968) in Fig. 2A and the length/depth regression of Jackson (1976) in Fig. 2B indicate a range of ratios associated with depth-limiting flows. In deep water, by contrast, dune growth is not limited by water depth. Dunes will continue to grow in response to increases in mean flow velocity until the critical suspension threshold for a given grain size is reached (see below).

3. The role of grain size

If at all, subaqueous flow-transverse bedforms will reach their maximum potential size in deep water only, i.e. where the maximum height or spacing corresponds to the H/d or L/d ratios outlined above. To define maximum size as a function of grain size, a large number of dune crests were sampled across a deep water dune sequence of the southeast African continental shelf. In each case the dune height and spacing were recorded. Altogether, a grain-size range of about 0.2-0.6 mm was covered. Plotting dune heights against grain size produced a point scatter with a well-defined upper height limit which increased with increasing grain size. Knowing the dune spacing, then maximum potential height of each dune was determined by the relationship defined in Fig. 1A. The maximum dune heights for the associated grain sizes were then plotted into the height vs. grain-size diagram, the points producing a well-defined upper bounding line. This newly generated relationship was then transformed into the diagrams illustrated in Fig. 3A and 3B.

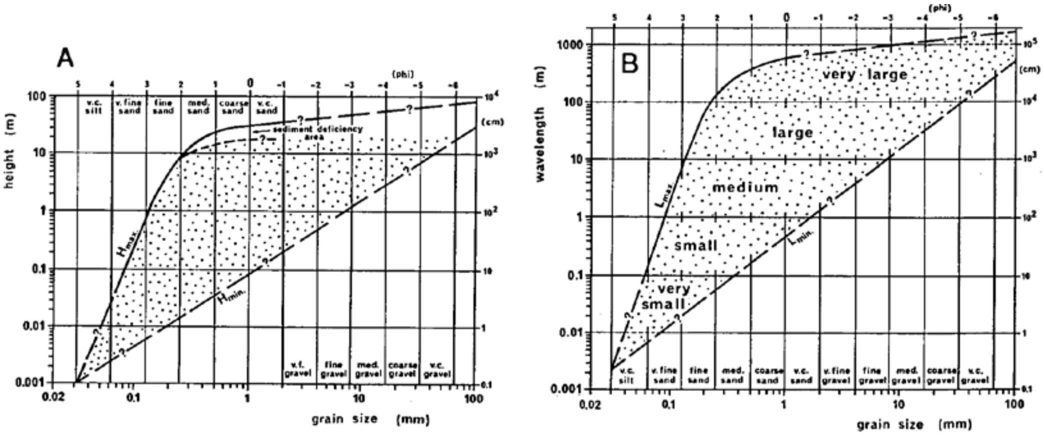

Fig. 3. Maximum dune height (A) and maximum dune spacing (B) as a function of grain size.

The log/log diagrams show that for grain sizes up to about 0.25 mm the maximum heights and spacings of flow-transverse bedforms (ripples and dunes) increase rapidly in linear log/log fashion. Between 0.25 mm and 0.5 mm a transition zone is defined, before at grain sizes above 0.5 mm maximum dune heights and spacings once more increase in linear log/log fashion, but now at a much lower rate. It should be noted that the behaviour of ripples can not be distinguished from that of dunes in this respect.

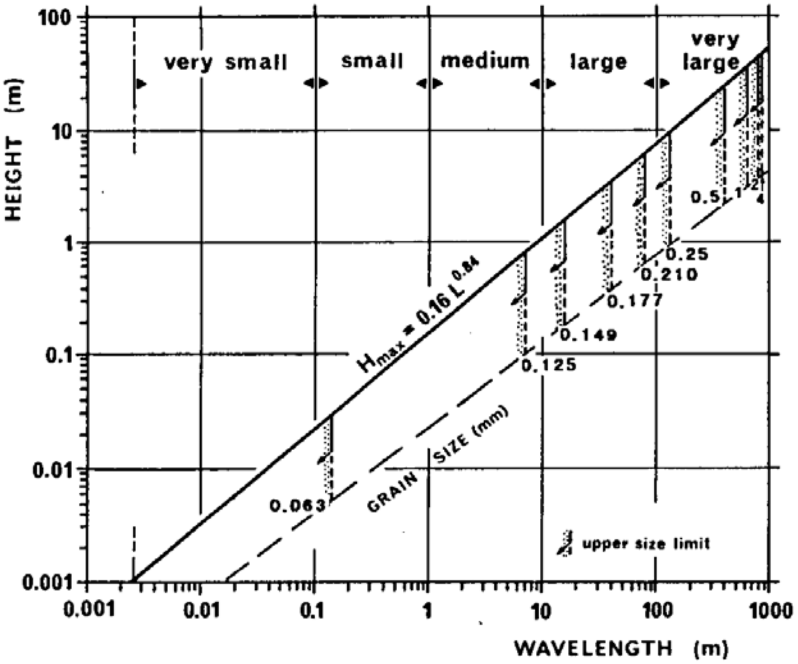

Fig. 4. Dune height versus dune spacing as a function of grain size. Note the progressive and quasi-logarithmic arrangement of increasing grain-size limits with increasing bedform size.

Adding the grain size limits to the height/spacing diagram reveals a clear pattern (Fig. 4). The larger the grain size, the larger the maximum potential dune size. In order to achieve maximum dune size for a given grain size, the water depth has to be correspondingly deep and the flow velocity correspondingly high. The pattern along which maximum potential dune size increases as a function of grain size is illustrated in the table below. Thus:

$D = 0.063$ mm: $H_{max} \approx 0.028$ m $L \approx 0.14$ m

$D = 0.125$ mm: $H_{max} \approx 0.8$ m $L \approx 7$ m

$D = 0.250$ mm: $H_{max} \approx 9.0$ m $L \approx 130$ m

$D = 0.500$ mm: $H_{max} \approx 24.0$ m $L \approx 380$ m

$D = 1.000$ mm: $H_{max} \approx 30.0$ m $L \approx 600$ m

4. Flow velocity as a limiting factor

In the context of this paper it would be of interest to define a range in which flow-transverse bedforms evolve from their initiation to the point of beginning destruction. Ripples or dunes begin to form when the bed shear stress exceeds the critical bed shear stress as defined by Shields (1936) by a small amount. A modified equation relating mean settling velocity to critical shear velocity for any water temperature and grain sizes up to about 0.5 mm on the basis of the Shields Criterion has recently been generated by Krögel and Flemming (1998). Thus,

$$\mathbf{u_{*cr} = (0.482\ [((\delta_s - \delta_f)/\ \delta_f)\ \nu\ g]^{0.282}) * (0.15\ w_s^{0.5}) + 0.61}$$

where u_{*cr} is the critical shear velocity (cm/s), δ_s is the particle density (g/cm^3), δ_f is the fluid density (g/cm^3), ν is the kinematic viscosity (cSt), g is the acceleration due to gravity (cm/s^2), and w_s is the particle settling velocity (cm/s). The critical condition at which bedforms begin to develop can thus easily be estimated from the settling velocity of the bed material, thereby defining the lower limit.

More difficult is the determination of an upper limit. As shown by Flemming (this volume), dune growth proceeds by amalgamation, in the course of which a sediment deficit of about 40% has to be compensated by lowering the base level through trough scouring. This means that dunes would not be able to grow any further once 40% of the bed sediment bypasses the crest in suspension. The data on suspension transport of Sundborg (1956) and Graf and Acaroglu (1966) suggest that approx. 40% of a bed sediment would be in suspension when the particle settling velocity is equal to the shear velocity. From this follows that dunes should cease to grow once the settling of the bed material equals the shear velocity at the crest (i.e. when $\mathbf{w_s = u_*}$) and that any further increase in the flow velocity would gradually transform the dune into an upper plane bed. It is not clear what the plan form of a dune looks like when this point is reached. Most probably it corresponds to the situation where a dune has become fully three-dimensional. In terms of equivalent settling diameters and a water temperature of 20°C, the approximate critical values are:

$D = 0.063$ mm: $u_* \approx 0.33$ cm/s

$D = 0.125$ mm: $u_* \approx 1.15$ cm/s

$D = 0.250$ mm: $u_* \approx 3.20$ cm/s

$D = 0.500$ mm: $u_* \approx 7.63$ cm/s

$D = 1.000$ mm: $u_* \approx 15.34$ cm/s.

At these grain-size specific shear velocities bedform growth comes to an end, the corresponding maximum potential dune sizes being listed above and illustrated in Fig. 4.

Discussion and conclusions

The data presented in this paper reveals an intricate relationship between the various parameters involved in the generation, growth and size limitations of subaqueous flow-transverse bedforms. It seriously challenges the notion that ripples are fundamentally different from dunes. Water depth is shown to play a role in limiting dune growth in shallow water, but has no function in deep flows. Dune growth is ultimately limited by a grain-size dependent shear velocity defining the transition from predominantly bedload transport to predominantly suspension transport. This criterion applies equally to shallow, depth-limited flows and deep water conditions, highlighting the fact that bedforms can only grow in relation to increasing flow velocities and on condition that the flow is not depth-limited. As a consequence, maximum potential bedform sizes are larger in coarse sediments than in fine sediments. This is consistent with observations in the field. Furthermore, flow-transverse bedforms grow in steps by the amalgamation of two or more smaller ones to form the next larger one.

Although a number of details are still obscure, a coherent picture is now beginning to emerge. Taken together, the critical factors involved in the development and growth of flow-transverse bedforms would appear to be best accommodated by a kinematic wave theory.

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