On the dimensions of depth-independent, simple subaqueous dunes

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Abstract
In the Grådyb tidal inlet (Danish Wadden Sea) simple, medium to large dunes, which are superimposed on large to very large dunes, increase in size with decreasing grain size under quasi-constant mean flow conditions. Mean dune height increases from about 0.1 m to 0.4 m and mean dune length from about 7 m to 11 m over a distance of about 1.5 km. The mean tidal range is ca. 1.5 m. The dominant dynamics are ebb oriented and almost constant along the study reach. The dominant velocity is 1.01 m s^{-1} over a mean depth of 11.85 m. The hydraulic roughness is 0.12 m and the dominating friction velocity 0.058 m s^{-1}. The water depth is more than one order of magnitude larger than the height of the superimposed dunes. These dunes are thus regarded as "free", i.e. depth-independent. This suggests that the established relationships between dune dimensions and grain size are not merely a local phenomenon. In order to translate the results into more general statements, the algorithms relating bedform dimensions to grain size in the study area, have been recalculated to accord with the form-corrected Shields parameter (θ'). In this way, dune dimensions have for the first time been directly related to both grain size and free stream velocity in a deep flow system.

Introduction
Dunes and ripples are commonly distinguished on the basis of their scaling or non-scaling with flow depth (e.g. Yalin, 1972; Allen, 1984; Ashley, 1990). Ripples are defined as small bedforms (length, L < 0.6 m) which do not scale with water depth, whereas dunes are larger and scale with water depth. This distinction has consistently ignored numerous, well documented examples where dune dimensions were found to be independent of flow depth (e.g. Flemming, 1978; Jackson, 1976; Dalrymple et al., 1978; Dalrymple, 1984; Ashley, 1990; Harbor, 1998; Carling et al., 2000 a&b). The simple fact that compound dunes exist, contradicts the depth-scaling argument. If the largest compound dunes scale with water depth, where does that leave the smaller, superimposed ones? And, if these scale with water depth, how can the compound dunes be orders of magnitude larger? At the other end of the scale, countless experiments in small laboratory flumes the world over have demonstrated that ripples are not always independent of water depth. In terms of their size, all flow-transverse bedforms generated in small flumes are by definition ripples, in spite of the fact that they clearly scale with water depth, as revealed by contracting water surfaces over their crests. As a consequence, the criteria by which ripples and dunes are supposed to be distinguished are inherently suspect.

In other words, if flow depth is small enough, any bedform will scale with it, simply because depth limitation forms a natural upper boundary, and serves as an upper limit for bedform growth of any kind. In most laboratory flumes, the maximum water depth is typically <0.5 m. As a result, dunes with heights greater than about 10 cm are prevented from developing. It is therefore not surprising that the largest bedforms in flume studies are found to scale with flow depth. By contrast, dunes observed on the ocean floor at depths of 100s-1000s of metres (e.g Kenyon & Belderson, 1973; Lonsdale & Malfeit, 1974; Kuijpers et al., 2002) exhibit a wide range of dune sizes. These must evidently be controlled by other factors than water depth. The only meaningful alternative is that under such circumstances the dunes are scaled by the mutual relationship between flow dynamics and form response. For obvious reasons this relationship should be highly dependent on grain size.

Bedforms recorded in the Grådyb tidal inlet on the west coast of Denmark (the northern part of the Wadden Sea) revealed that under virtually constant hydrodynamic conditions the height and length of simple dunes, as well as compound dunes was essentially controlled by grain size (Bartholdy et al.; 2002). The primary objective of the present paper is to present, in a more general form, the dynamics and grain-size control of secondary, superimposed simple dunes, as a case study of the generation and dynamic response of free, i.e. depth-independent dunes. The study was supported by the Danish Science Research Council Grant # 21-01-0513.

Dynamics and dunes at the study site

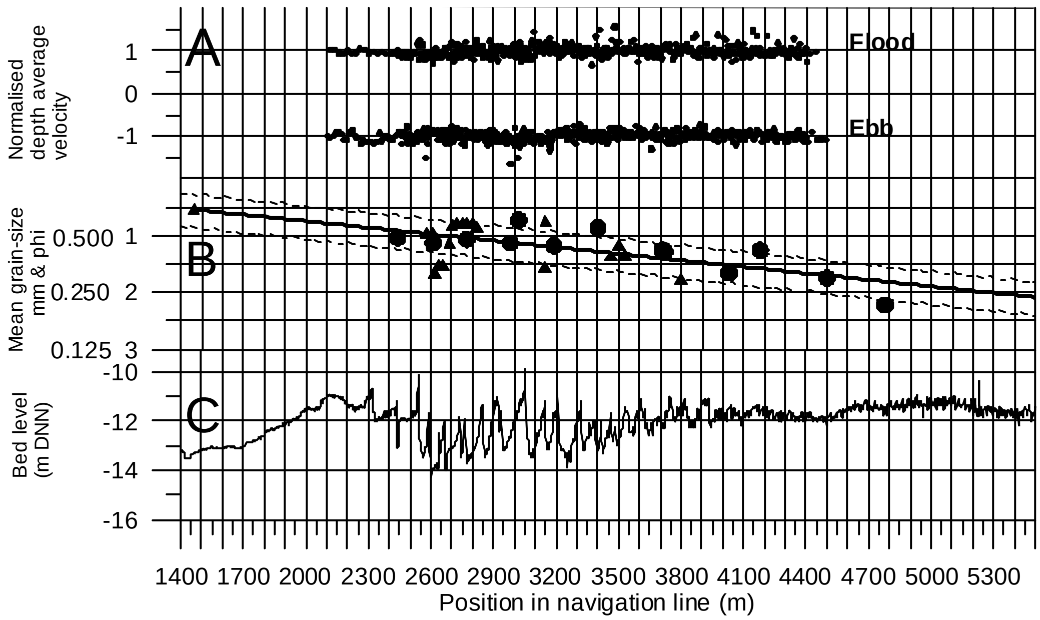

Fig. 1 - Dynamics, mean grain-size and dune dimensions along the study reach. The ebb direction is from left to right. **A)** Instantaneous (ADCP measurements along the surveyed line, the total measuring period was approx. 12 min) normalised depth averaged velocity along the centre line of the inlet. The data represents 5 ebb and 4 flood situations recorded during near-peak velocity. Each velocity is normalised against the section mean velocity of the single data set. **B)** Mean grain size of bed samples along the study reach. Triangles correspond to samples collected in 1992, circles to samples from 1999. The full line represents the linear regression of mean grain size versus length in the navigation line, while the stippled lines indicate +/- one standard error of the estimate (equal to +/-0.292 phi). **C)** Topography along the study reach recorded on 19 May 1999. (From Bartholdy et al. 2002).

The mean tidal range in the Grådyb inlet is close to 1.5 m. Mean grain size of the bed material along the centre line of the inlet throat decreases from 0.6 mm in the inner part, to 0.3 mm in the outer part (Fig. 1). Two dune populations are present: large to very large compound dunes, and medium to large simple, superimposed dunes. Both dune populations are essentially two-dimensional with straight to slightly

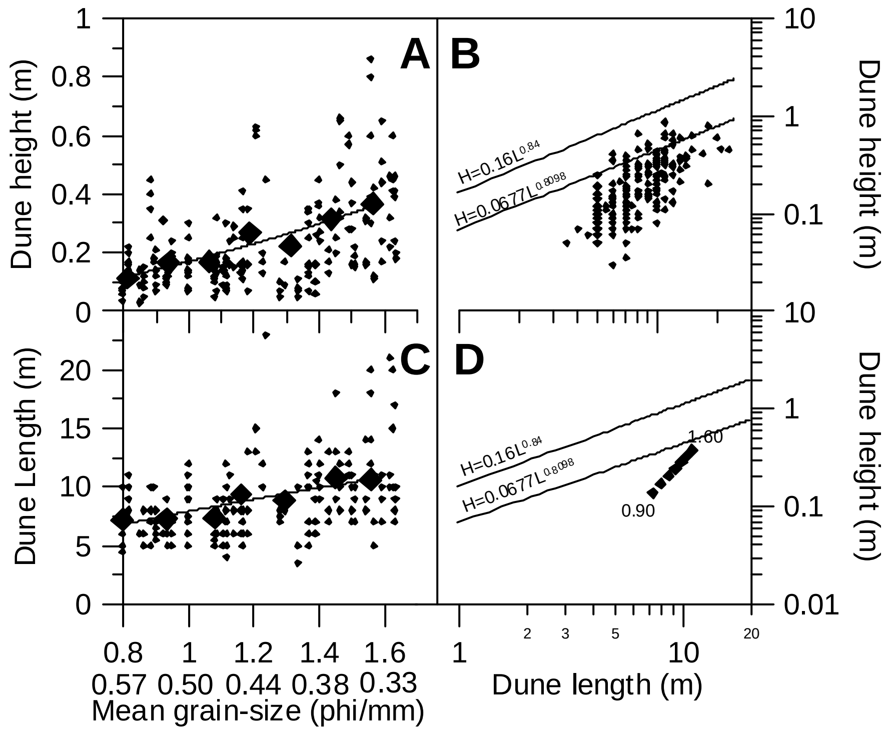

Fig. 2 - **A)** Dune height and **C)** dune length of the simple dunes in the Grådyb inlet (1991-1994) as function of mean grain size. The mean grain size is calculated on the basis of the position along the survey line and the relation shown in Fig. 1. Only bedforms from the upper (¼) part of the large compound bedforms are included. The large symbols indicate the group mean values calculated at 1/8-phi intervals. **B)** Dune height versus length for all measured simple bedforms. **D)** Dune height versus length for the average bedforms as defined by the regression lines in A) and C), grain size varied from 0.90? to 1.60? (0.53 mm – 0.33 mm). From Bartholdy et al. (2002).

curved crest lines. The tidal currents are of similar magnitude along the entire study reach. Sediment transport occurs during both ebb and flood, the latter being less vigorous than the former. As a result, the inlet as a whole is ebb dominated, the dominant ebb current reaching 1.01 m s^{-1} at a mean water depth of 11.85 m, The hydraulic roughness (ks), derived from accurate velocity measurements 0.11 m and 0.50 m above the bed, was found to be 0.12 m. This corresponds to a dominant friction velocity (uf) of 0.058 m s^{-1}. The dominant dynamics are defined as the flow velocities above and below which half of the sediment transport (using the total load formula of Engelund & Hansen, 1972) is achieved. The calculation of the dominant dynamics is based on 6 weeks of continuously measured tidal currents at a fixed position in the inlet.

The large to very large dunes display distinct flood caps during the flooding tide but remain overall ebb-oriented, whereas the medium-sized dunes reverse their direction during each tide. The downstream dimensional evolution of the large dunes is complex, switching from initial growth to progressive decline followed by renewed growth in length but continued decline in height. This latter degradational phase begins in the middle of the survey reach and continues seaward until the large forms disappear completely.

At the same time, the outer channel section becomes dominated by medium- sized simple dunes which grow in size with decreasing grain size. There is no correlation between dune dimensions and water depth.

The dimensions of both compound and superimposed simple dunes are correlated with grain size. Being more than one order of magnitude smaller in height than the flow depth, the simple dunes are regarded as "free" in the sense that they are not restricted by depth. The algorithms shown in Fig. 2 A & C link grain size (sieve) to dune height, as well as to dune length. The regressions are based on group mean values, calculated at 1/8-phi intervals:

$$H = 0.17 \cdot Mz_{?}^{\,1.68} \qquad (R^2 = 0.92) \qquad (1)$$

$$L = 7.9 \cdot Mz_{?}^{\,0.68} \qquad (R^2 = 0.83) \qquad (2)$$

Dune heights (H) and lengths (L) are in metres and the mean grain size is in phi-units. These mean conditions describe a H/L-ratio which falls well below the line suggested by Flemming (1988):

$$H = 0.0677 \cdot L^{0.8098} \qquad (3)$$

However, as is evident from Fig. 2 B & D, the ratio increases with decreasing grain size, and the level described by Eq. 3 is reached in the outer fine grained end of the survey line. The two lines merge at L = 12.3 m and H = 0.51 m which, according to equations 1 and 2, corresponds to an average grain size of 1.92 phi (0.265 mm). The results therefore suggest that, under similar dynamic conditions, free (i.e. not depth-limited) dunes increase in height and, to a somewhat lesser extent, also in length with decreasing grain size. The fact that Eq. 3 and Eq. 1 & 2 give similar results in the medium/fine sand range, could imply that the large, superimposed simple dunes in the database on which Eq. 3 is founded primarily consist of fine sand.

Dimensions of simple free dunes vs. grain size and dynamics

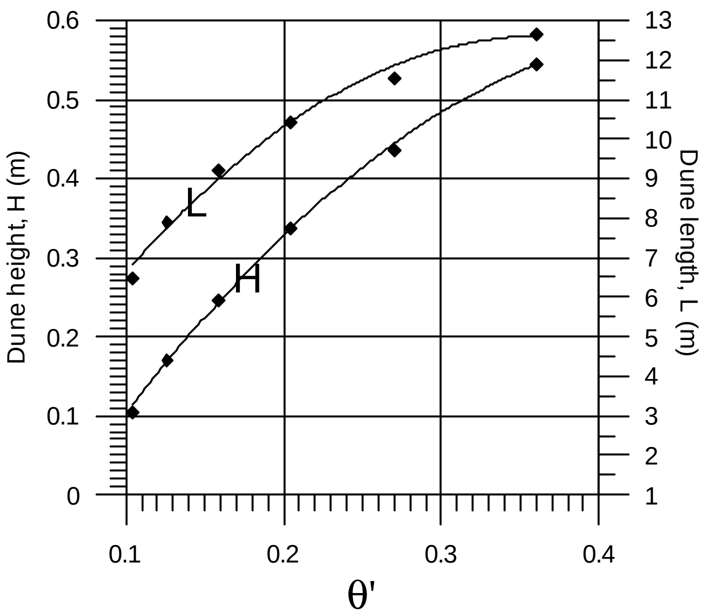

Figure 3. Dune height (H) and length (L) of simple dunes in the rådyb inlet as function of the form-corrected Shields parameter.

As bedform dimensions relate to transport conditions in general, a direct comparison based on grain size alone will be misleading under changing dynamic conditions. In order to compensate for this, the grain sizes in Eq. 1 & 2 were recalculated into the form-corrected Shields parameter (θ'), based on the dominant friction velocity. In this procedure, the general Shields parameter,

$$\theta = uf^2 / [(s\text{-}1)\cdot g\ d_{50}] \qquad (4)$$

is transformed into the form-corrected Shields parameter, which considers skin friction only, following the method of Engelund & Hansen (1972). Thus

$$\theta' = uf'^2 / [(s\text{-}1)\ g\ d_{50}] = 0.06 + 0.4\ \theta^2 \qquad (5)$$

where uf is the friction velocity (m s^{-1}), uf' is the form-corrected friction velocity (m s^{-1}), s-1 is the dimensionless submerged density of quartz (1.65), g is acceleration due to gravity (9.82 m s^{-2}), and d_{50} is the mean grain size (m). The relationship between average dune heights and lengths and the form-corrected Shields parameter is illustrated in Fig. 3.

A test of best fit relationships between θ' and H and L (linear, logarithmic, exponential, power, and polynominal fits were included) resulted in the following two parabolic equations, both with an R^2 of >0.99 (Fig. 3):

$$H = -3.45\ \theta'^2 + 3.29\ \theta' - 0.19 \qquad (6)$$

$$L = -86.21\ \theta'^2 + 62.69\ \theta' + 1.17 \qquad (7)$$

The advantage of using θ' as the independent variable is that this parameter is directly related to sediment transport (e.g. Meyer-Peter & Müller, 1948, Engelund & Hansen, 1972, Engelund & Fredsøe, 1976, Fredsøe & Daigaard, 1992). It is thus the most obvious parameter to be related to bedform development. The disadvantage is that this parameter is difficult to handle, especially as in many deeper water situations the free stream velocity, which would be located well above the bed features, may be the only available dynamical indicator. On the other hand, dunes in deep flows react to the free stream velocity and therefore adjust to the overall flow conditions. It is thus desirable to search for a more direct way of relating flow velocity to bedform dimensions.

Rearranging Eq. 4 and 5 with respect to the logarithmic velocity profile, i.e.

$$Uz = [8.5 + 2.5\ \ln(z/ks)]\ uf \qquad (8)$$

results in,

$$uf' = (0.9722\ d_{50} + A\cdot U_z^4/d_{50})^{1/2} \qquad (9)$$

and

$$\theta' = (0.9722\ d_{50} + A\cdot U_z^4/d_{50}) / [(s\text{-}1)\cdot g\cdot d_{50}]$$

$$= (0.9722\cdot d_{50} + A\cdot U_z^4/d_{50}) / [16.203\cdot d_{50}] \qquad (10)$$

where $A = 0.0247 / [8.5 + 2.5\ \ln(z/ks)]^4$, Uz is the velocity (m s^{-1}) at level z (m) above the bed, and ks (m) is the total (form + skin) equivalent "sand" roughness of the bed. In the Grådyb inlet, the depth-averaged velocity level is close to 4 m above the bed (0.368 times dominant depth). At this location, the current data used in this study was collected. Furthermore, this level is close to that above which the velocity change becomes minimal, but is still close to the region in which a logarithmic velocity profile can be assumed. Therefore, 4 m above the bed was chosen as the reference level in Eq. 9 and 10. According to the empirical formulas suggested by Soulsby 1990 (cited in Soulsby, 1997), a reduction of

ks (m)	M ($m^{1/3}$ s^{-1})	B (s^2 m^{-1})
0.02	48.8	$0.072 \cdot 10^{-6}$
0.04	43.4	$0.101 \cdot 10^{-6}$
0.06	40.6	$0.124 \cdot 10^{-6}$
0.08	38.7	$0.145 \cdot 10^{-6}$
0.10	37.3	$0.164 \cdot 10^{-6}$
0.12	36.2	$0.182 \cdot 10^{-6}$
0.14	35.2	$0.200 \cdot 10^{-6}$
0.16	34.5	$0.216 \cdot 10^{-6}$
0.18	33.8	$0.232 \cdot 10^{-6}$
0.20	33.2	$0.248 \cdot 10^{-6}$
0.22	32.7	$0.263 \cdot 10^{-6}$
0.24	32.2	$0.278 \cdot 10^{-6}$
0.26	31.8	$0.293 \cdot 10^{-6}$
0.28	31.4	$0.308 \cdot 10^{-6}$
0.30	31.0	$0.322 \cdot 10^{-6}$

Table 1 - Corresponding values of the total (form + skin) equivalent “sand” roughness of the bed (ks), the Manning number (M, equal to $25.4/ks^{1/6}$ and to 1/n, where n is the Manning coefficient), and B from Eq. 11.

the free stream velocity by 10 % will transform this into the velocity at 4 m above the bed within an error of +/- 7 % at water depths between 10 and 25 m. Above 25 m, resistance due to bed roughness is regarded as negligible. This procedure is therefore regarded to be valid for all depths above 10 m within an error window of 7 %.

Based on this, Eq. 10 becomes:

$$\theta' = (0.9722\, d_{50} + B\, U_8{}^4/d_{50}) \,/\, [16.203\, d_{50}] \qquad (11)$$

where $B = 0.90^4 \cdot A = 0.6561 \cdot A$, and U_8 is the free stream velocity. The parameter B varies with surface roughness as shown in Table 1 below.

If, as a role of thumb (e.g. Soulsby, 1983), ks is supposed to be in the range 0.1 m to 0.2 m when under the influence of bedforms, then the corresponding range of B would be $0.164 \cdot 10^{-6}$ s^2 m^{-1} to $0.248 \cdot 10^{-6}$ s^2 m^{-1}. For a free velocity of 1.1 m s^{-1}, and a grain size of 0.50 mm, Eq. 11, 6 and 7 predict corresponding ranges in dune height and length of H = 0.15 m to 0.23 m and L = 7.42 m to 8.62 m, respectively. A change in grain size to 0.25 mm would, under similar dynamic conditions, give a range of H = 0.48 m to 0.58 m and of L = 12.19 m to 12.31 m, respectively.

This demonstrates that the results based on Eq. 11, 6 and 7 are only moderately dependant on ks (which is always difficult to determine). Calculations like these form the basis of the diagrams presented in Fig. 4 & 5, from which the heights and lengths of free simple dunes can be determined for flow depths >10 m on the basis of mean grain size and free stream velocity. The choice of ks = 0.12 m in this diagram is based on the data from the Grådyb tidal inlet.

It should be noted that the algorithms are calibrated for water temperatures of about 10 - 15°C and grain sizes in the range of 0.6 - 0.3 mm. Deviations from these conditions may change the calibration constants if other scaling effects than those laid down in θ‘ have an influence on the result. Unfortunately, only little published data is available on free simple dunes together with the corresponding dominant dynamics. We are currently collecting such data and hereby invite interested colleagues to participate in building up a data base on free subaqueous dunes in order to improve our knowledge about bedform generation and dynamics, and, in particular, to obtain improved versions and calibrations of Eq. 6 and 7.

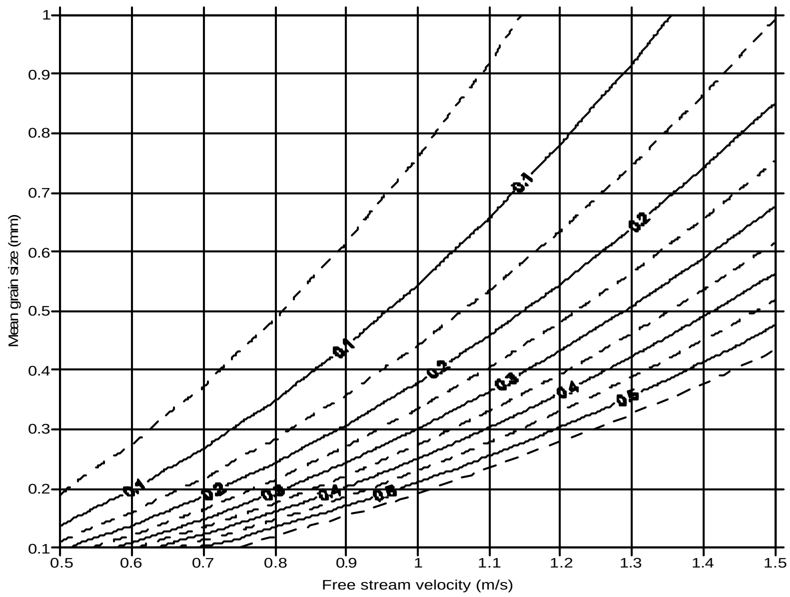

Fig.4 – Height (m) of simple free subaqueous dunes as function of grain size and free stream velocity. Based on Eq. 11, 6 and 7, with B = 0.182 * 10^{-6} s^2 m^{-1} which corresponds to an overall hydraulic roughness of ks = 0.12 m.

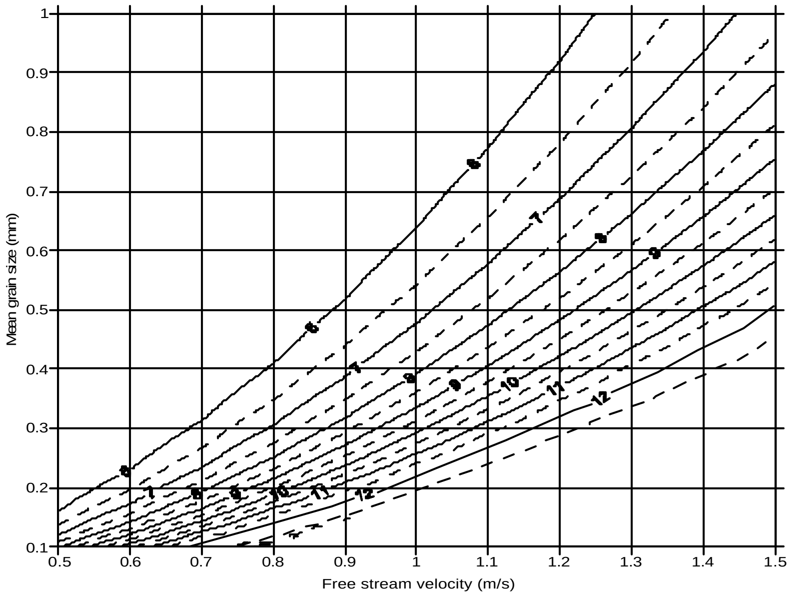

Fig.5 – Length (m) of simple free subaqueous dunes as function of grain size and free stream velocity. Based on Eq. 11, 6 and 7, with B = 0.182 * 10^{-6} s^2 m^{-1} which corresponds to an overall hydraulic roughness of ks = 0.12 m

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