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Sorting in grain flows at the lee side of dunes

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Abstract

Sediment sorting at the lee side of ripples, dunes and bars has already been recognized long ago. A predictive model of the sorting is necessary but unavailable for implementation in sediment transport models for sediment mixtures. Relevant processes in sedimentological and physical literature are reviewed and compared to the sparse data of sediment sorting. A synthesis is given of the most important variables governing the sorting processes for the benefit of future experimentation and modelling. These variables are the sorting (standard deviation, skewness and bimodality) of the sediment mixture delivered to the brink point, the height of the dune or bar relative to the average grain size of the mixture, the velocity of the flow above the brink point relative to the settling velocity for all grain size fractions, and the frequency of the grain flows. In addition, the initiation mechanism and frequency of the grain flows affect the pattern and effectiveness of sorting.

Keywords: Subaqueous dunes; Grain flows; Sediment mixtures; Sediment sorting; Fluvial deposits

1. Introduction

A well known feature of fluvial sediments is the cross-stratified deposit, caused by the propagation of the bedforms by discontinuous grain flows of bed load sediment at the lee side of a dune (Allen, 1963, 1984) and by settling from suspension on the foreset (Jopling, 1965; Hunter, 1985b). The angle of the lee slope of such bedforms is in the order of the angle of repose of the sediment, which is about 25–40°, whereas the height of these bedforms ranges from 0.01 to 3 m. Within a cross-stratified set the sediment is often sorted vertically. The gravel usually is mainly deposited on the lower part of the lee slope, whereas the finer grades are predominantly deposited in the upper part. The result is an upward fining deposit with cross-stratification.

Although this sorting principle related to grain flows is well known, a mathematical description of the process is unavailable. Yet, the sorting process is relevant for sediment transport prediction as follows. Part of the resulting fining upward sequence of the largest dunes that occurred during a discharge wave is preserved in the bed. Furthermore, the sediment is entrained and deposited size selectively in the dune troughs, which also results in an upward fining deposit. This combined deposit is the source for sediment

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entrained during the next discharge wave, which will depend on the relict vertical sorting and on the depth from which it is entrained (Klaassen et al., 1987; Kleinhans, 2001). The entrainment and deposition depth of the sediment depends on the dune trough level below the average bed level and therefore on the dune height (Ribberink, 1987; Blom et al., 2003). Thus subsequent discharge waves of decreasing magnitude will leave the upward fining cross-stratified sets at depths related to the concurrent dune height (Kleinhans, 2001). A discharge wave of high magnitude will reset the bed and leave a fresh upward fining deposit. Vertical sorting in a river bed is thus intimately linked with sediment transport, which is the rationale herein for studying the deposition processes at the lee side of dunes. Herein the emphasis is thus on dunes, although most of the processes may be relevant as well for bars, Gilbert-type delta's, growing volcanic scoria cones, etc. In addition, certain insights may be relevant to the hydraulic interpretation of sedimentary and volcanological deposits.

The local vertical sorting is obviously strongly linked to the environmental origin of the sediment. Friedman (1979) provides an overview of statistical measures describing grain size distributions of sediments. By plotting these measures against each other, Friedman was able to demonstrate that the sands of various origins plot in different fields in the graphs. This strongly suggests that the origin of sands can be determined on basis of their statistical fingerprint only. Thus, the environment of sand deposition controls the grain size distribution, which in turn controls and limits the potential for local sorting. The focus of this paper is on local sorting. For the sake of understanding the local sorting processes, artificial laboratory mixtures and bimodal sandy gravels are considered as well, which renders a comparison with the plots by Friedman out of the scope of this review. The environmental origin and sorting of these sediments is reviewed in Sambrook Smith (1996) and Powell (1998).

The objective of this paper is to review (physical) mechanisms and explanations for sediment sorting and deposition processes at the lee side of dunes, specifically for poorly sorted sediment mixtures of sand and gravel. This is done in the following steps. First, basic sedimentological definitions and well-known processes and deposits are defined. Second, the sparse data sets of vertical sorting in bedforms from literature are presented and discussed. Third, the main vertical sorting processes are discussed in detail, and secondary effects are summarized. Fourth, it is attempted to distill the most important variables that govern grain flow and sorting behaviour, to serve as a guideline for future systematic experiments and field measurements. The recent work of physicists has been given ample attention because of the promising results but also for pointing out simplifications that cause the applicability of highly idealised physical principles to natural sediments to be limited. The results are combined in a conceptual model that qualitatively predicts the vertical sorting curves in various sediments and conditions.

2. Basic sedimentological definitions, units and processes

2.1. Bedforms and transport

Based on literature, basic sedimentological units and processes are identified for dunes (see Figs. 1 and 2). They are generalized and their implications for vertical sorting in the river bed are discussed below in more detail. Dunes are here loosely defined as asymmetrical bedforms with a height and length in the order of magnitude of the water depth, as opposed to ripples of which the dimensions are scaled by the grain size. Ripples occur only in sand with grain sizes below 0.7–0.8 mm (Southard and Boguchwal, 1990).

The dune height is defined as the vertical distance between the trough and top. The brink point is the location at which the flow separates from the bed surface, causing a turbulent counterflow in the lee of the dune (see Fig. 2). The zone at which the flow impinges on the bed surface is called the reattachment zone. Downstream of that zone the flow is in the downstream direction and is called coflow, which is herein taken roughly as restricted to the trough zone. 'Trough' and 'top' are used to denote the zones above the deepest bed height and below the uppermost bed surface height, respectively, in this paper. With 'bed surface', the local interface between water or air and sediment is denoted, whereas 'average bed level'

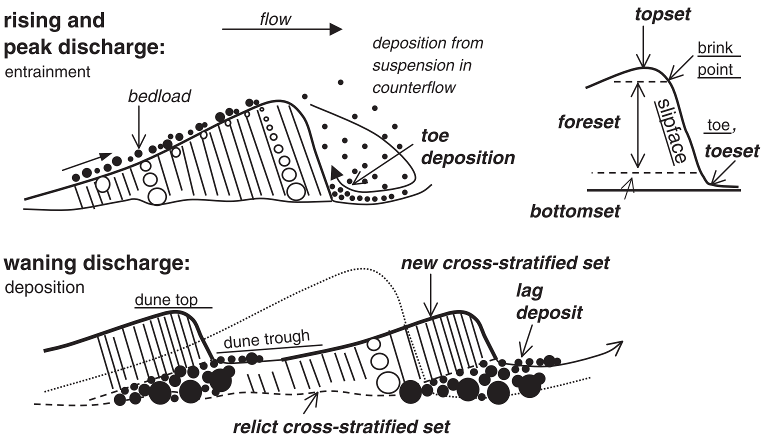


Fig. 1. Basic definitions of depositional units in river dunes in peak and waning discharge (after Kleinhans, 2001). The dunes leave a lag deposit in the river bed below their troughs, which consists of coarse sediment that is no longer mobile.

denotes the level of the bed averaged over the whole dune length.

The sediment is transported over the dunes in three different basic ways:

1. sliding, rolling and saltating of grains over the bed due to the shear stress exerted by the flow, which is called bed load sediment,
2. suspended sediment transport, which occurs when the saltation height and length of the grains is much larger than the grain size, and
3. gravity-driven movement of sediment downslope, i.e. grain flows, usually at an angle that is larger than the angle of repose.

2.2. Sorting by grains rolling, grain flows or grain fall and the resulting deposits

Within dunes, three basic depositional units can be distinguished, being a bottomset, a foreset c.q. cross-stratified set and a topset (see Fig. 1). Bed load sediment is transported on top of the dune, and may be preserved as a topset, which has an erosional boundary with the underlying sediment. In addition, the largest particles are partially mobile and form an armour layer on top of the dune or in the trough. This armour layer protects the underlying dune or bed to some extent against erosion.

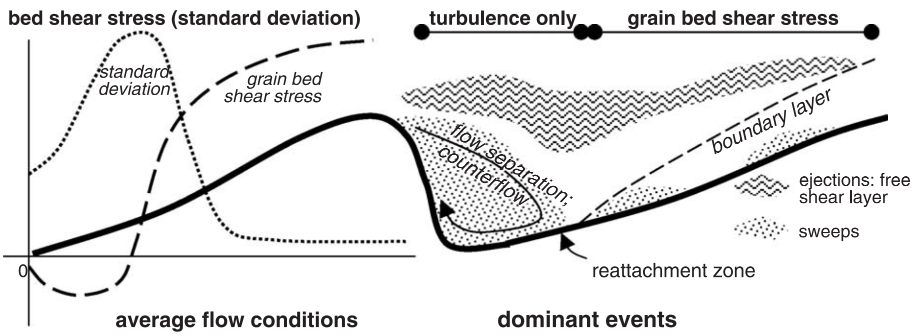


Fig. 2. Flow conditions over dunes. The average shear stress on the grains (dune surface) is negative (upstream directed) in the trough region, and positive and growing downstream of the reattachment zone. The standard deviation of that grain shear stress is maximal near the reattachment zone, where the turbulent flow variations are the largest. In terms of turbulent flow structures, in the trough zone the counterflow is dominated by sweeps, while the free shear layer flow above the dune tops is dominated by ejections. Downstream of the reattachment zone and upstream of the point where the flow separates from the dune top (called brink point), a boundary layer develops (after Bennett and Best, 1995).

Sediment that arrives at the brink point of the dune is partly deposited on the lee slope. A finer part of the sediment is suspended, to be deposited on the lee slope, in the trough zone or on the stoss side of the downstream dune.

It is important to distinguish between two possible directions of sorting (see Fig. 3) (Allen, 1984):

1. tangential: the direction of the flow of water or grains,
2. perpendicular: upward normal to the plane of flow.

The deposition in a cross-stratum of the largest grains near the toe of a dune and the smallest grains near the top gives a net fining upward sorting in the whole dune. Thus vertical sorting in dunes is the result of tangential sorting, which is, for the gravity driven grain flows, parallel to the cross-strata.

Furthermore, the fining or coarsening of sediment is defined as follows (see Fig. 3) (Allen, 1984). Sorting in the tangential direction is called normal when the largest particles are deposited upstream of the smallest grains, as is the case in downstream fining rivers. Sorting in the perpendicular direction is called normal when the smallest particles are on top of the largest, for example in the fining upward deposit of suspended sediment settling in waning flow. Sorting in the tangential direction is called reverse when the largest grains are deposited downstream of the smallest grains. Thus the upward fining in a dune is a case of reverse tangential sorting. Sorting in the perpendicular direction is called reverse when the largest particles are located on top of the smallest, as is the case in river bed armouring.

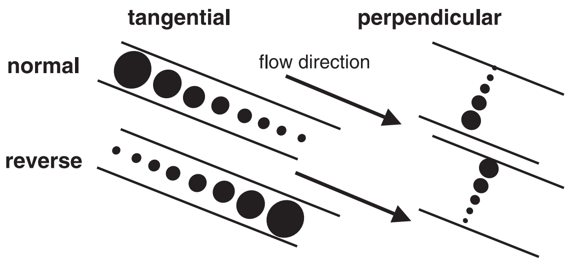


Fig. 3. Definitions of directions of sorting in four cases, in this case drawn in a cross-stratum, according to Allen (1984). Tangential and perpendicular refers to the direction of sorting relative to the direction of the moving sediment. Normal and reverse refers to the fining or coarsening trend in the deposit.

Three important types of sediment movement and deposition in foresets on the lee side of bedforms are identified between Jopling (1965), Allen (1984), Hunter (1985b), Carling and Glaister (1987) and others, given in order of increasing sediment mobility: individual grains rolling down on the lee slope, grain flows, and grain falls. A grain flow refers to a gravity-driven mass of grains that moves downward while the individual moving grains collide and interact (Lowe, 1976). A grain flow is a laminar, high-concentration cohesionless flow in the terminology of Postma (1986). The sediment on the lee slope will accumulate until the angle of repose of the sediment is exceeded. (The angle of repose is sometimes called angle of internal friction, to denote the critical angle of a mass of sediment (internal friction) as opposed to that of the individual grains (repose).) Then the accumulated sediment will roll (individual grains) or flow (grain flow) down the lee slope of the dune. This gravity-driven movement stops at the toe of the lee slope, where the local bed slope decreases. The moving layer of sediment on the lee slope is deposited as a cross-stratum. A number of cross-strata are called the cross-stratified set, and the cross-strata are also called laminae. Cross-stratified sets may range in thickness from a few millimeters in ripples to more than 100 m in Gilbert-type deltas.

A grain fall on the other hand refers to the settling of individual, suspended grains from the flow, in which interaction between grains which move is much less important than the interaction between a moving grain and static grains on the lee slope. The grain fall process leads to decreasing deposition rates in the downstream direction from the dune top where the flow suddenly expands. The grain fall mechanism is not only the cause of the formation of the sediment mass prior to grain flow initiation, but also of the toeset and bottomset deposition. Suspended sediment is partly captured in the counterflow and settles on the lee slope and in the trough to form a bottomset. The part of the bottomset at the toe of the lee slope is called the toeset when it is not buried (yet). The sediment in the trough is transported both upstream and downstream, depending on the position relative to the reattachment zone. Both the counterflow and the coflow may form ripples. With very small flow energy, the bottomset may be preserved when the dune migrates over it by deposition of cross-strata at its lee side on top of the bottomset. With higher flow energy, an armour layer may form because the smaller grains are winnowed from the bed and are suspended, while the largest grains of the sediment are partially mobile or immobile.

Obviously, the description above is simplified, and the number of processes, interactions and possible combinations between the deposits is large. Different processes are governing the formation of bottomsets, foresets and topsets. The formation of foresets and bottomsets is herein emphasized, since this is the most commonly found deposit in sand–gravel and gravel bed rivers, where vertical sorting is most relevant, and because these are the most important units in an active river bed with dunes whereas bottomsets are not often preserved.

The sorting within rolling grain, grain fall and grain flow deposits is obviously different. In the grain fall, roughly the largest grains are deposited near the brink point and the smaller ones further downslope. Grains may roll down individually and the largest grains may be transported further downslope due to their larger momentum. In the grain flow, the grains drag the neighboring grains and a number of sorting processes occur that are discussed later. It is therefore relevant to assess the importance of both grain fall and flow for the sorting in the end products. It can be hypothesized that the general mobility of the sediment (shear stress or Shields number) governs the ratio between grain fall and flow. Thus fine-grained sediments, which are much easier suspended, will have a much stronger grain fall deposition all over the lee slope (Fig. 4a), especially in wind-blown deposits (Nickling et al., 2002), whereas coarse-grained sediments have little or no grain fall deposition on most of their lee slope, resulting in a grain flow dominated deposit (Fig. 4b), or, for the coarsest sediments, rolling grain deposits.

Not many papers have specifically addressed the problem of quantifying vertical sorting within a dune, although some work has been done on the sorting within individual grain flows and other granular mass flows (Iverson, 2001). Some present data on the sorting, and a group of physicists attempted to model the vertical sorting for grain flows in air. In Table 1, the available data used in this paper are summarized. In the next section, the available data and observations (from Allen, 1963; Blom et al., 2000; Dillingh, 1990; Kleinhans, 2002; Love et al., 1987; Ribberink, 1987 and Termes, 1986) are reviewed with special attention to the relative importance of individual grain rolling, grain falls and grain flows and other possible sorting processes. Subsequently, the three types of sediment movement and deposition on lee slopes (grain fall,

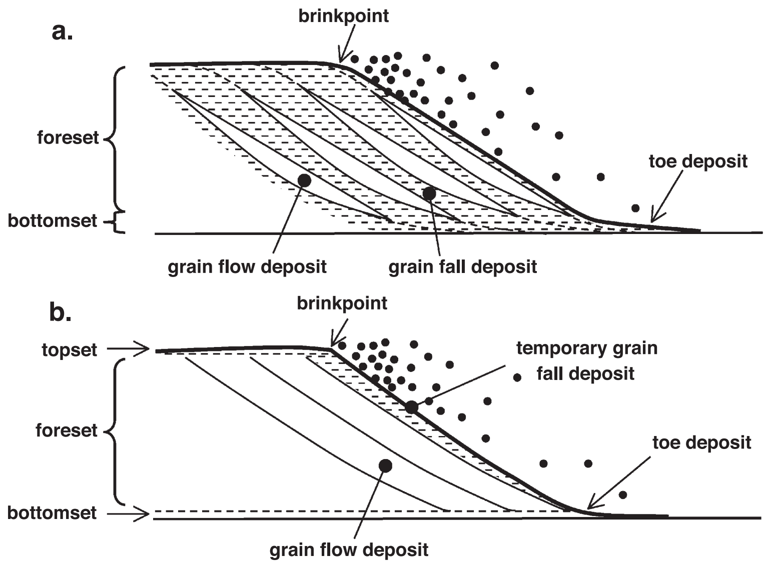


Fig. 4. (a) Sorting and definitions in dune deposits after Hunter (1985b). (b) Modified sorting in dune deposits for much lower sediment mobility (little suspension) where only grain flow deposits are preserved.

Table 1
Literature on vertical sorting data in grain falls and grain flows

Author(s) and year	Sediment	Conditions
Data sets used herein		
Allen (1963, 1970)	sand	small flume
Blom et al. (2000)	trimodal sand–gravel	large flume
Dillingh (1990)	sand	field active dunes
Kleinhans (2002)	sand–gravel	large flume
Love et al. (1987)	sandy–gravel	field relict dunes after flood
Ribberink (1987)	sand–gravel	large flume
Termes (1986)	sand–gravel	small flume, Gilbert-type delta
Hunter and Kocurek (1986)	sand	small flume, Gilbert-type delta
Descriptions		
Allen (1984)	sand	small flume
Bagnold (1954)	sand	laboratory, air
Bak et al. (1988)	sand	laboratory, air
Boersma et al. (1968)	gravelly sand	field deposits
Carling (1996)	gravel	field relict dunes after flood
Carling and Glaister (1987)	gravel	flume
Hunter (1985a,b)	sand	small flume, Gilbert-type delta
Jopling (1965)	sand	small flume, Gilbert-type delta
Klaassen (1987, 1991)	gravelly sand	large flume
Nemec (1990)	gravelly sand	field, Gilbert-type delta
Shaw and Gorrell (1991)	sandy–gravel	field relict dunes after flood

Modelling and related experimenting with artificial sediments

Author(s) and year	Phenomena	Model
Boutreux (1998)	segregation	microscopic grain interactions
Boutreux et al. (1998)	stratification and segregation	microscopic grain interactions
Cizeau et al. (1999)	stratification and segregation	continuum flow
Koeppe et al. (1998)	stratification and segregation	microscopic grain interactions
Makse (1997)	stratification and segregation	stability analysis
Makse et al. (1997a)	stratification	–
Makse et al. (1997b)	stratification	–
Makse et al. (1998)	stratification and segregation	(detailed measurements)
Makse and Herrmann (1998)	stratification and segregation	microscopic grain interactions

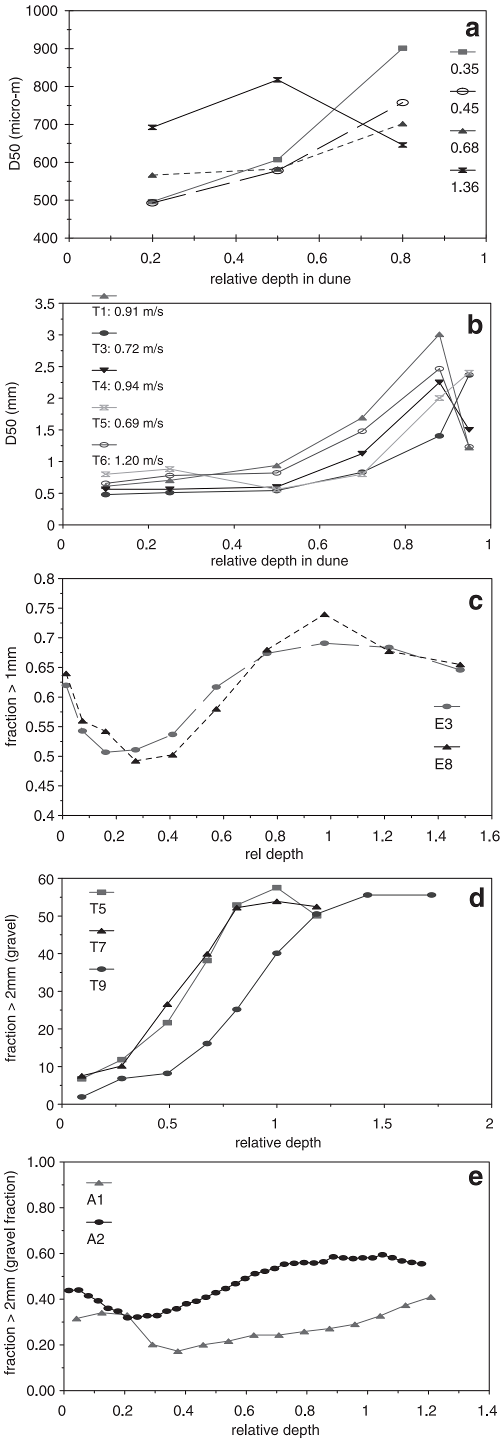
individual grain rolling and grain flow) are discussed in detail.

3. Sorting data in literature

3.1. Vertical sorting in foresets in laboratory experiments

Allen (1963) experimented with sand in a small laboratory flume, in which a single dune or delta-like feature was created. Allen found that sediment was deposited in a wedge on the upper lee slope of the dune. This wedge of sediment failed above a certain angle and then created a new cross-lamina. Above a certain transport rate, the wedge no longer formed and there were grain flows continuously. Using a sand with a D50 (median grain size) of 590 μm, a D10 of 350 and a D90 of 1200 μm, he found that the D50 in the dune varied with a factor 1.5–2 between dune top and toe (see Fig. 5a). The general trend was fining upward, which decreased with increasing flow velocity and sediment transport and grain flow frequency. With the highest flow velocity (1.36 m/s) and continuous grain flows, the trend vanished or even inverted partly.

Termes (1986) created a Gilbert-type delta about 0.1 m high in a small flume, in which he studied the vertical sorting formed at the lee side of the delta (see Fig. 5b). The sediment had a D10 of 320 μm, a D50 of 750 and a D90 of 3600 μm. An upward fining trend was found, with a sharp decrease in the lower part of the delta. An armour layer was observed on the top surface of the delta. Termes reported that ripples of coarse sediment (here meant as partly gravel) migrated over the top of the delta, but since ripples only exist in sediment finer than about 700 μm, these bedforms probably have to be classified as bed load sheets. Also, in experiments T1, T4 and T6 (the highest flow velocities, see Fig. 5b) the lower lee slope was enriched with sand from suspension, and sand was also deposited on the bed just downstream of the lee slope, and later overrun by the delta foresets. These fine deposits can be interpreted as toesets and bottomsets. It is not clear from the data whether the foreset itself was enriched with the sand, or whether the lowest sampled layer included both an unenriched lowest foreset and the underlying sandy bottomset and



thus was finer than the layer of foreset material just above the lowest one.

Ribberink (1987) sampled the vertical sorting in dunes of about 0.04 m high after experiments in a large flume with a bimodal sediment with modes at 0.78 and 1.19 mm (see Fig. 5c). He found that the coarse sediment which was immobile or less mobile than the finer sediment, was deposited as a lag near the level of the deepest dune troughs. Furthermore, the sediment at the top of the dune was rather coarse. This may be interpreted either as the bed load sediment on top of the dune, possibly as a less clear sorting in the upper part of the dune, or as an armour layer on top of the dune.

Klaassen (1991) and Blom and Kleinhans (1999, see also Kleinhans, 2002) did comparable experiments as Ribberink (1987). The data of Klaassen are not shown here. The Blom and Kleinhans experiments were done with a coarser and less bimodal sediment than in the Ribberink experiments, with a D50 of 1.8 mm and a Dmax of 16 mm. In these experiments (T5 with 0.7 m/s and 28 mm dune height, T7 with 0.8 m/s and 57 mm dune height, T9 with 0.7 m/s and 49 mm dune height) a clear fining upward trend was found

Fig. 5. Vertical sorting measured in experiments. The dune or bar top is on the left-hand side of the graphs, and the base is on the right-hand side. A horizontal line means no fining or coarsening upward trend at all, and a line with a positive slope means a strong fining upward trend. (a) Vertical sorting in the dune in Allen (1963). Data is derived from his Fig. 12. The fining upward trend decreases with increasing flow velocity and grain flow frequency. (b) Vertical sorting in the Gilbert-type delta in Termes (1986), experiments T1, and T3 to T6. The flow velocity is given as well to indicate the conditions. In experiments T1, T4 and T6 a bottomset can be observed in the lowest part of the delta. (c) Vertical sorting in the dunes in Ribberink (1987) in his experiments E3 and E8. The sediment is divided into two grain size fractions: coarser and finer than 1.0 mm. The top of the dune shows the presence of coarse bed load sediment, and at the level of the dune troughs there is a lag deposit of gravel. (d) Vertical sorting in the dunes in Kleinhans (2002), Blom and Kleinhans (1999), experiments T5, T7 and T9. The sediment is here divided into two grain size fractions (sand and gravel), coarser and finer than 2.0 mm. The level of the dune troughs agrees with the level of the armour layer in T5 and T7, whereas in T9 the armour layer of T7 can still be observed. (e) Vertical sorting in the dunes in Blom et al. (2000) in experiments A1 and A2. The sediment is here divided into two grain size fractions (sand and gravel), coarser and finer than 2.0 mm. The top of the dune shows the presence of coarse bed load sediment and a gravel lag layer.

without the coarsening at the dune top as observed by Ribberink (see Fig. 5d). The main mechanism of foreset formation was grain flows. It was observed that many grain flows were rejuvenated by overrunning subsequent grain flows, and that protruding large grains were captured by the overrunning grain flows to be transported even further down the lee slope. However, halfway up the crest of the dune, an upstream-facing coarse surface gravel lag was observed on many dunes, which sank to the trough level as the dune migrated. A clear armour layer was observed at the level of the dune troughs. In the last experiment (T9) the armour layer formed in T7 was still present, and a new upward fining accumulation of lag deposits formed on top of this armour layer as the dune height decreased. Thus the vertical sorting in these experiments clearly are the result of both sorting in the grain flows at the lee of dunes, and selective deposition of gravel in the dune troughs.

Blom et al. (2000) sampled the vertical sorting in and below the dunes in a large flume (see Fig. 5e). The sediment was trimodal, with modes at 0.74, 2.0 and 6.1 mm. From base to top, the general trend is fining upward. The sediment just below the dune top, however, shows an increase in grain size. This is interpreted as a combination of bed load transport and a gravel lag layer on top of the dunes. This may expected to be a thin layer, but was here smeared out in the averaging procedure; the given curves are averages of more than 10 cores at several locations on the dunes. Comparison of tests A1 (lower flow velocity, dune height 24 mm) and A2 (higher flow velocity, dune height 62 mm) indicates that with the higher flow velocity not only more gravel is entrained, but also that the sorting curve in the lower 2/3 of the dune changes from straight to convex.

Recently, a number of highly controlled laboratory experiments with grain falls and flows of granular mixtures in air has been done by Makse and coworkers (Makse, 1997; Boutreux, 1998; Boutreux et al., 1998; Makse and Herrmann, 1998; Makse et al., 1997a,b, 1998), by Koeppe et al. (1998) and by Lecocq and Vandewalle (2000) and Thomas (2000) and many others. The experiments were mostly done with a vertical Hele-Shaw cell, which is (in Makse's case) a flume of width 0.5 cm, length 30 cm and depth 20 cm, in which the sediment is poured at one upper corner. Bimodal sediments were used with different forms and size ratios. Two mutually almost exclusive types of sorting occurred (discussed in detail in Section 5.2):

- segregation which results in reverse tangential sorting of small and large round grains. This segregation is almost perfect for Dlarge/Dsmall>1.5; otherwise, it is more gradual. Segregation leads to a strong fining upward trend but no striping characteristic for many natural sedimentary structures.
- cross-stratification with reverse perpendicular sorting of large cubic grains and small round grains. With a decreasing size difference, the stratification becomes less clear and vanishes at Dlarge/Dsmall < 1.5. Stratification yields almost no fining upward trend but a 'striped' sediment pattern.

The fact that segregation and cross-stratification are mutually exclusive in these experiments seems to be at variance with the common observation that both can occur in the same set in nature; therefore, these experiments must be interpreted with caution.

3.2. Vertical sorting in foresets in rivers

Love et al. (1987) measured vertical sorting in relict gravelly megaripples of 0.12 m high that were formed during a flash flood in the Conveyance Channel of the Rio Grande (Central New Mexico) (see Fig. 6). An armour layer on top of the bedforms was observed, and ripples migrated over the armour layer. The lower foreset was interpreted by Love et al. to be reworked in the waning flow of the flood: the winnowing of sand from the lower foreset lead to an excellent sorting of the gravel at that near-trough level in the bedform.

Dillingh (1990) measured the vertical sorting in sand dunes in the river IJssel near Deventer (The Netherlands) (see Fig. 6b). The sediment has a D50 of 500–550 μm, a D10 of 340 and a D90 of 1300 μm. The dunes had a height of 1–1.5 m and their crests continued over the full width of the river channel. The vertical sorting is widely varying and the trend is only slightly fining upward. Allen (1963) on the other hand found a clear sorting in a comparable sediment, except for the high velocity with continuous grain flows. Although his results refer to a small, artificially created dune in laboratory conditions, they imply that the grain flows in the IJssel might have been continuous as well because of their negligible sorting. However, since the dunes at that location have a rather long adaptation time, it is quite possible that a single dune consists of the deposits of several flow stages and amalgated dunes, which would blur any sorting trend within one active foreset.

Summarizing the laboratory and field observations:

1. The sorting trend in foresets is stronger in wide mixtures (larger mixture standard deviation computed arithmetically from the semi-logarithmic distribution) than in almost uniform sediment.
2. A higher frequency of individual grain flows decreases the sorting trend. This frequency is related to the celerity of bedforms (~ bed load transport in m^3/s m divided by dune height) and the thickness of individual grain flows.
3. There seem to be two different modes of sorting: cross-stratification (striping pattern parallel to slip face but no fining upward sorting) and segregation (fining upward sorting but no striping pattern).
4. Secondary phenomena affecting the sorting trend are deposition of suspended sediment on the foreset and in the trough, armouring on the dunes, and gravel lag deposition below the dunes in changing flow conditions.

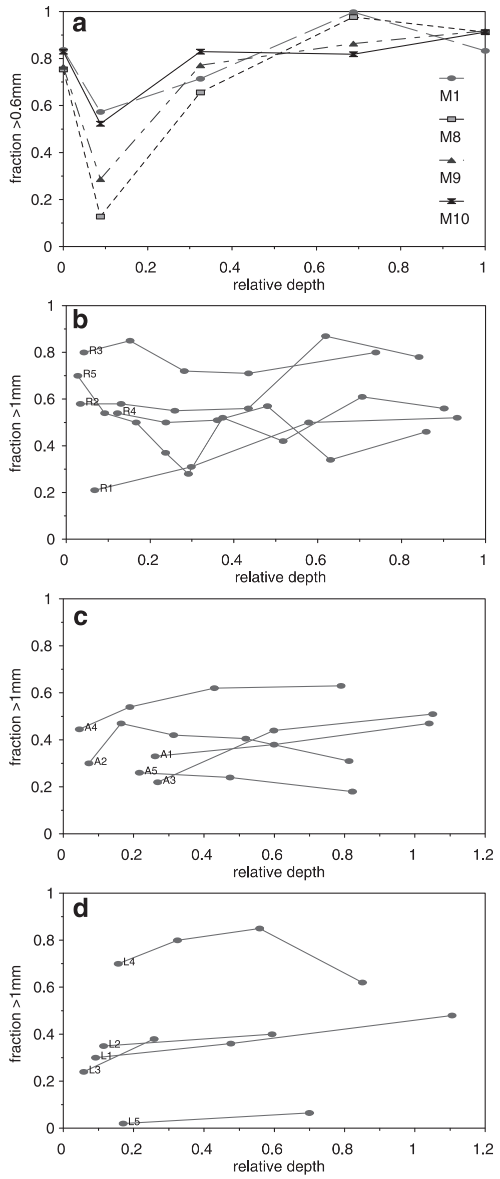


Fig. 6. Vertical sorting measured in natural river dunes. The dune top is on the left-hand side of the graphs, and the base is on the right-hand side. A horizontal line means no fining or coarsening upward trend at all, and a line with a positive slope means a strong fining upward trend. (a) Vertical sorting in four gravelly bedforms (M1, M8, M9 and M10) in the in the Conveyance Channel of the Rio Grande (Love et al., 1987). The sediment is divided into two grain size fractions: coarser and finer than 0.6 mm. The armour layer can clearly be seen, and some indication of a slightly finer bottom set is visible in two of the four dunes. (b–d) Vertical sorting in 15 sand dunes in the left (b), middle (c) and right (d) side of the river IJssel, The Netherlands (Dillingh, 1990). Numbers refer to individual dunes. The sediment is divided into two grain size fractions: coarser and finer than 0.5 mm. Curves R1–R5 are located in the right half of the river, L1–L5 in the left half and A1–A5 on the river axis.

In the next section, the three principal modes of sediment motion and deposition on the lee slopes are discussed, based on literature and compared to the laboratory and field data sets presented here. These are grain fall (deposition from bed load and suspended load on the foreset), individual grain movement on the lee slope, and grain flows as defined in Section 2.2.

4. Grain fall process and deposition

A sediment-laden flow arriving at the brink point decelerates rapidly due to the strong water depth increase. The sediment is deposited from this flow on the foreset slope after a short path of suspension. Large grains are deposited immediately downstream of the brink point, while smaller grains may take more time to settle and are deposited lower on the foreset slope. Thus the concentration and settling rate of sediment decreases in downstream direction from the brink point. Allen (1970) and Hunter (1985b) found that the decrease of settling rate for a single grain size follows a power function or exponential function with a faster decay for larger grain sizes. The result of this settling pattern is a sediment wedge with the form of this function (Hunter, 1985a,b). This wedge builds up until the angle of static repose is exceeded. Then the mass fails and initiates individual grains rolling or a grain flow (see Fig. 7E).

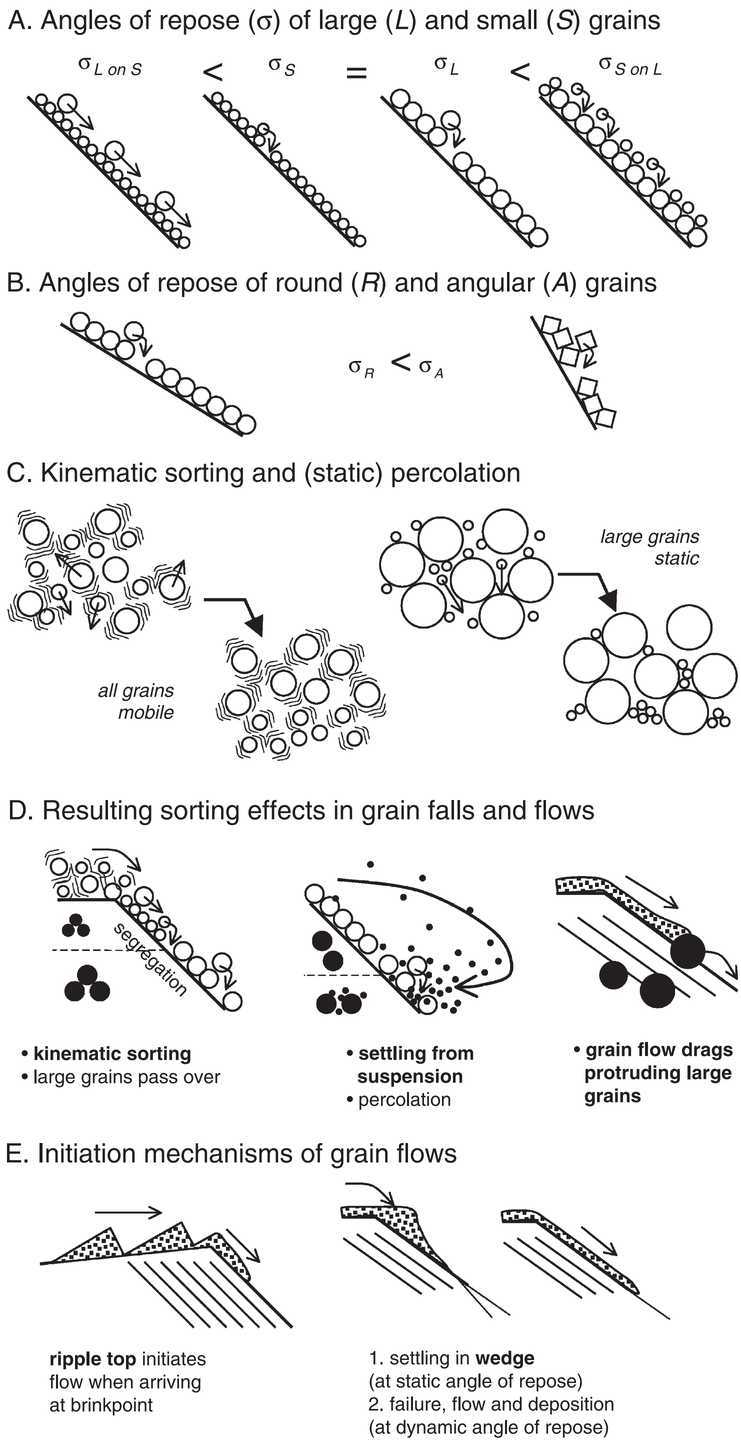
The relation between the flow velocity above the brink point and the settling velocity of the sediment is well known. When the ratio of the bed shear velocity u^* and the fall velocity w_s of the sediment is larger than a certain value, the grains are suspended. Since the boundary between saltating bed load transport and suspended transport is a gradual one, the critical value depends on the definition of suspension. Bagnold (1966, cited in Van Rijn, 1993) found that fully developed suspension occurs when $u^*/w_s>1$, whereas Engelund (1965, cited in Van Rijn, 1993) found $u^*/w_s>0.25$ for initial suspension. Van Rijn (1993) defined suspension as the shear velocity at which the grains have saltation jump lengths larger than 100 grain diameters, which was experimentally found to be $u^*/w_s>0.4$.

Experimental evidence is provided by Jopling (1965) and Allen (1968). Jopling measured the deposition of suspended sediment in the lee of a laboratory Gilbert-type delta (i.e. a fluvial deposit with its downstream slope at the angle of repose, deposited from a river entering a basin with a much larger depth than the river, e.g. a lake or an ocean). He found that the amount, as well as the grain size, of deposited sediment decreases from brink point to trough. A combination of the vertical distribution of flow velocity and suspended sediment concentration was used to calculate the settling velocities and flow path of grains of different sizes. The results of that calculation agreed reasonably with the measurements. Allen (1968) extended this approach and found that the concentration of settling sediment decreases downstream as a power function with power $\sim u/w_s$. Furthermore, grains with a large settling velocity are deposited mostly very near the brink point. A comparable pattern with normal grading is found in pyroclastic flows where the grain-size and density sorting is also governed by the settling (Druitt, 1995).

Obviously, the settling pattern also depends on the flow pattern, which is highly turbulent in the lee zone of a negative step, Gilbert-type delta or dune. High-frequency flow measurements with laser-doppler instruments above fixed dunes reveal consistent spatial patterns of flow turbulence (e.g. Bennett and Best, 1995; McLean et al., 1999) (see Fig. 2). The water circulates in the lee, resulting in a backward or return flow near the foreset slope. The length of this zone generally is four to five times the height of the step, delta or dune. In the case of dunes, any deposition of sediment downstream of the reattachment zone is not so likely to be preserved. The stoss side of dunes is erosional and the bottomset is probably more often than not removed (Allen, 1968). Therefore, the model of Jopling cannot be used for river dunes, but still might be useful for bars and Gilbert-type deltas. The counterflow may even rework the deposits on the lower foreset and in the dune trough, which is discussed in a next section.

When the sediment wedge on the upper foreset exceeds the static angle of repose, the sediment mass in the wedge fails and starts to move downslope (see Fig. 7E). The downslope movement refers to individual grains, when only little sediment is involved, and to a grain flow, when so many grains are involved that they start to behave as a flow. The transition between individual grain movement and grain flow is obviously gradual, but for clarity the two are discussed separately.

Fig. 7. Concepts of sorting mechanisms. See text for explanation. (A) The relations between the angles of repose of uniform sediment, large grains on small grains and small grains on large grains. (B) The relations between the angles of repose of rounded and angular sediment. (C) Difference between kinematic sorting and percolation is that all grains are in motion in the former, while the large grains in the latter are static. The opportunity for percolation depends solely on the pore space between the large grains, whereas the opportunity for kinematic sorting also depends on the kinetic energy of the sediment. (D) Three sorting mechanisms in sediment motion at the lee side of a bedform. (E) Initiation mechanisms of grain flows according to Hunter (left) and Allen (right).



A. Angles of repose (σ) of large (L) and small (S) grains
σ L on S < σ S = σ L < σ S on L
B. Angles of repose of round (R) and angular (A) grains
σ R < σ A
C. Kinematic sorting and (static) percolation
all grains mobile
large grains static
D. Resulting sorting effects in grain falls and flows
segregation
• kinematic sorting
• large grains pass over
• settling from suspension
• percolation
• grain flow drags protruding large grains
E. Initiation mechanisms of grain flows
ripple top initiates flow when arriving at brinkpoint
1. settling in wedge (at static angle of repose)
2. failure, flow and deposition (at dynamic angle of repose)

5. Sorting in foreset deposits from individual rolling grains

5.1. The role of angles of repose

During the descent of individual grains down the lee slope, the weight and angle of repose as well as the relative size of the rolling and fixed grains determine the probability of deposition on the slope (see Fig. 7). Richardson (1903, cited in Allen, 1984) already argued that large grains 'experience' a smooth surface when rolling over small grains, but a rough surface when rolling over grains of their own size. Mobile grains that are large with respect to immobile grains in the bed have a very small probability of encountering a niche in which they may deposit. Thus, when a grain flow is in motion, irregularities below it are relatively large to small grains which may lead to termination of their motion. The large grains on the other hand continue rolling and thus pass over the surface.

In addition, a large, and therefore heavier, grain gains more momentum than a small grain in its downwards movement. Consequently, the grain has less probability of deposition because it bounces out of possible niches. As a result, the largest grains are deposited near the toe of the lee slope, and the smaller grains near the top (see Fig. 7A). This process is known as overpassing (although the term has been used for other, related phenomena as well). Overpassing on the lee slope is not under influence of the flow, but solely attributed to the difference in size between the large and small grains.

It can be expected that these processes are affected by grain shape and angularity. Since more angular grains have a higher angle of repose, they will come to rest sooner than rounded grains which have a lower angle of repose, for instance at the top of the slope (see Fig. 7B and the next section).

Makse and coworkers (Makse, 1997, 1998; Boutreux, 1998; Boutreux et al., 1998; Makse and Herrmann, 1998; Makse et al., 1997a,b, 1998) and Koeppe et al. (1998) used these principles in a mathematical model of grain flows and sorting (although they were unaware of Richardson's, Allen's and Bagnold's works). They were able to reproduce the observations discussed in the section devoted to laboratory and field observations herein (see Fig. 8). The model by Makse and coworkers only explicitly includes the grain weight of the two grain species and the angles of repose of the pure grain species and of the two species on each other. The latter two were not even included in the model by Koeppe et al., who therefore reproduced the phenomena with even less variables in the model. In the next section, their results are discussed in detail.

5.2. Physical modelling of highly idealised conditions

Makse and coworkers and Koeppe et al., found two mutually almost exclusive types of sorting occur in strictly bimodal sediment: segregation and stratification. The segregation is due to the difference in grain size and the like-seeks-like effect, which results in reverse tangential sorting only. The like-seeks-like effect refers to the mechanism that large grains preferentially come to rest on a surface of grains with comparable sizes, because on a surface of smaller grains there are no pockets of that size that could accommodate the large grains, but only a surface of small grains that is felt as a smooth surface for the large grains. This segregation is almost perfect for Dlarge/Dsmall>1.5; otherwise, it is more gradual. The second type is stratification due to difference in grain form and therefore the angle of repose of each grain species and of the one on the other. For two grain species with a different form but equal size, the angle of repose is the largest for the most angular grain species. Thus the most angular grains are deposited on the top part of the lee slope, and the smoother grains on the lower part (see Fig. 7B). When the size of the angular grains is larger than the round grains, there is obviously an unstable situation: there is competition between size segregation and shape segregation. With large cubic grains and small round grains, a clear cross-stratification emerges. With a decreasing size difference, the stratification becomes less clear and vanishes at Dlarge/Dsmall < 1.5.

The explanation by Makse and coworkers is that with these grain species, there is a competition between size segregation and shape segregation. The size segregation would lead to reverse tangential sorting, whereas the shape segregation would lead to the roughest (cubic) grains in the top part of the lee and the smoothest (round) grains in the lower part. Consequently, the whole mixture flows down without significant tangential segregation. When reaching the bottom of the flume (or the trough of the dune), the

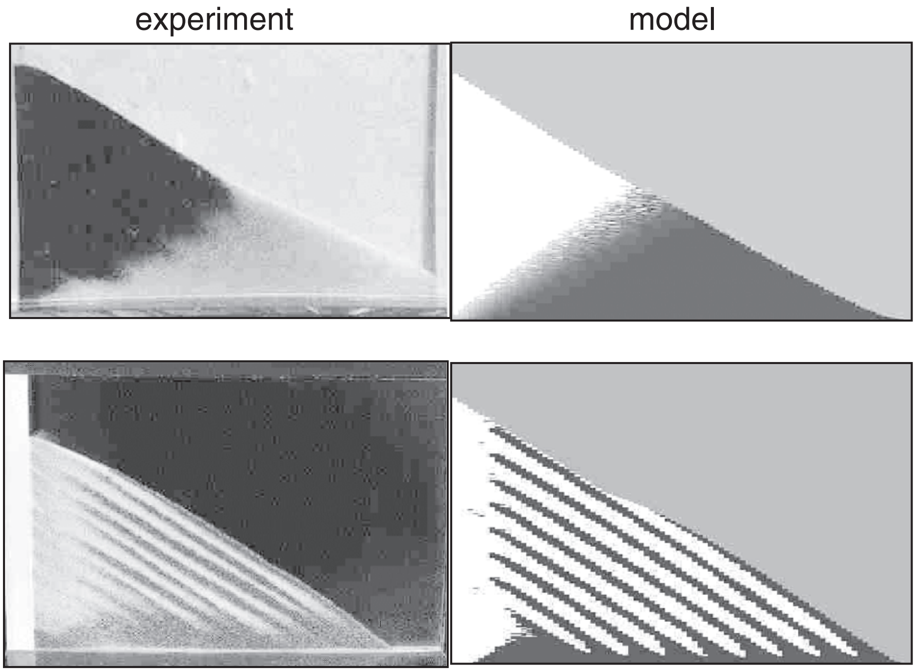


Fig. 8. Comparison of experimental (left) and modelling (right) results by Makse and coworkers (after Cizeau et al., 1999). Top panels: segregation of the two grain species. Bottom panels: stratification. See text for explanation.

small grains stop first. The reason is that the small grains on a mixture or on the large grains are more easily captured by the like-seeks-like effect mentioned earlier. The small grains stop first, large grains are deposited on top of the small, and a static pile (called kink) develops at the angle of repose of small grains on top of large grains. This angle of repose is larger than the angle of repose of pure grain species, which means that the steeper slope of the kink remains stable. The front of this kink moves up the slope as more grains are deposited on it, maintaining the reverse perpendicular sorting. This leads to the development of one cross-stratum. Obviously, stratification is quickly established by the like-seeks-like effect, as the whole slope becomes covered with large grains and the small grains of the next grain flow are easily captured on top of the large grains. The moving front also was observed by Allen (1972) in subaqueous sand dunes in a flume. Both Makse et al., and Allen observed that the kink moved at about the same velocity as the grain flow.

Before these concepts and model for highly idealised sediments can be applied to more natural field and flume conditions, it is worth questioning whether the results of the work by these physicists is representative for any natural condition. Their flume was only 5 mm wide, whereas the coarsest particles were 0.8 mm and the thickness of the grain flows up to 7 mm, suggesting that wall effects may be large. Makse et al., report that the effect of the wall was only that the angles of repose of the sediment were large compared to the case without walls. This increased angle of repose was fed into the model, but they found that the observed phenomena occurred for much lower angles of repose as well, suggesting that the qualitative results are independent of the magnitude of the angle of repose. Furthermore, the principal experiments were reproduced in a flume of double width with equal results. Therefore, they concluded that the wall effect has no effect on their conclusions. However, Koeppe et al., found a strong effect of the width of the flume: it determined the transition from stratification to segregation. In addition, Makse and coworkers found that segregation (tangential sorting) and stratification are almost mutually exclusive, whereas in natural sediments the combination has often been found. It would be strange if many observations in nature and laboratory should fall exactly in the small range Makse found in which both stratification and segregation occur; therefore, it is concluded that these experiments and models cannot without modification be applied to more natural conditions.

Koeppe et al. (1998) found that stratification may occur in bimodal sediment with the same angle of repose (both round grains). They were able to relate each cross-stratum to a single failure of the sediment wedge as described by Allen (1970). It may be that the formation of the wedge in Makse's experiments was inhibited by the large initial velocity of the grains, that were poured from a certain height into the flume. This has the effect that the sediment has an initial vertical velocity. The large grains gain more kinetic energy than the small, which may promote the segregation they found. At the brink point of more natural dunes, on the other hand, the sediment arrives with a horizontal velocity component only. The flow separates from the bed at an angle of about 10° (Wilbers, personal communication), whereas the angle of repose of the sediment is in the order of 30°. Thus the bed load sediment is dropped on the top of the lee slope and a wedge-shaped deposit forms (Allen, 1970), which was not observed by Makse. It is more likely that the mechanism as described by Allen occurs on natural dunes, because the wedge has been observed in a number of different settings, and because it explains the simultaneous formation of perpendicular and tangential sorting. The cross-stratification mechanism described by Makse and coworkers may be limited to a laboratory setting and need not play a dominating role in more natural dunes.

Makse and coworkers also studied the effect of grain shape. Angular grains have a larger angle of repose than round grains of the same size. Consequently, the angular grains are deposited on the upper lee slope while the round grains are deposited on the low lee slope, as was corroborated by numerical and analog experiments. This agrees with the findings of Carling and Glaister (1987), who found that the most angular grains were deposited on the upper part of the slip face, and the rounder grains on the lower part. Also Nemec and Postma (1993) found the oblate and blade cobbles preferentially on the upper slope of a debris fan.

This shape effect is explained as follows. For two grain species with different sizes but equal forms, the angles of repose of the pure species are equal. However, the angle of repose of the small grains on the large grains is larger, whereas the angle of repose of the large grains on the small grains is smaller. This is of course explained by the difference in size between the grain species; the large grains when rolling over the small grains, experience a smooth surface, whereas the small grains rolling over the large ones, experience a rough surface. Thus the large grains tend to end on the lower part of the slope, whereas the small grains end on the upper part. This trend is quickly amplified by the like-seeks-like effect, as the upper part of the slope becomes smoother for the large grains. The result is a reverse tangential sorting along the slope.

To summarize, in conditions with individual grain movement, the angles of repose of the grains on grains of their own size or different sizes determine their position on the foreset slope. This includes effects of grain shape. In addition, the formation and failure of a sediment wedge on the upper foreset slope is the steering mechanism in grain mobilisation. The demobilisation and deposition occurs from the bottom of the foreset slope to the top (kink moving up) as a compaction 'wave' of the sediment, which is initiated when the grains reach the bottom (dune trough). There may be two modes of deposition that exclude each other, stratification and segregation (see also earlier section about vertical sorting data sets in laboratory conditions), depending on the angles of repose of the grain species on each other.

6. Sorting in foreset deposits from grain flows

Two different stages in the grain flow are described. First the initiation is discussed, and the effect of the mode of initiation on the sediment sorting. Second the motion of, and sediment sorting in the grain flow itself are discussed.

6.1. Initiation of the grain flow

The initiation of grain flows has been ascribed to two different phenomena. These are ripples and bed load sheets arriving at the brink point of dunes, and the formation of a sediment wedge that fails above a certain angle (see Fig. 7E). They are discussed below and compared with empirical evidence.

Hunter (1985a) discussed the possibility of ripples being the initiator. He found that the frequency of grain flows was much larger than that of ripple passage. In addition, it can be argued ripples do probably not occur on the top of dunes, especially not on gravel dunes which occur in flows with a large energy. However, secondary dunes on top of larger primary dunes are often observed, and also dunes on top of bars (e.g. Mohrig, 1994). Concluding, ripples are probably not very important for the sorting in dunes. The sorting is therefore mainly a function of what happens on the lee slope.

Allen (1963, 1984) ascribed the regularity of the grain flow process and cross-stratification to the formation of a wedge of sediment on top of the lee slope (as discussed in the previous section). He found a difference between the static angle of repose and the dynamic angle of repose: the static angle of repose before failure is larger than the dynamic angle of repose at which the grain flow is deposited. The difference between the two angles is called the dilatation angle, because the dynamic angle is that of a dilated sediment mass, being the grain flow. Just after the deposition of a grain flow, a wedge of sediment will build up at the brink point until the static angle of repose is reached. Since the dilatation angle is more or less constant for a certain sediment, the process yields regular cross-strata of comparable thickness (neglecting suspended sediment settling). In very coarse sediment, the wedge has not been observed (Carling and Glaister, 1987), and grains dropped by the flow downstream of the brink point moved down the slope individually.

Disregarding the wedge, it has been suggested that grain flows are critically self-organized. Bak et al. (1988) describe how a subaerial pile of drying sand may show grain flows of all possible sizes, ranging from a few grains up to a length on the order of the slope length. They argue that the pile of sand is in a self-organized critical state and shows fractal behaviour of grain flow frequency versus size. The upshot is that the grain flows of small sizes occur much more frequently and the bigger it gets, the smaller the frequency. However, in the drying pile of sand the sand supply to grain flows is all over the slope, instead of only at the brink point as in moving dunes. This is confirmed by Allen (1963, 1970), who found that small grain flows occurred every now and then on the top of the lee slope, but these accumulated in the wedge (described before) to yield one large grain flow of regular size. Thus, the self-organized critical grain flowing process is repressed by the formation of the wedge, which is only a function of the dilatation angle.

Grain flows are limited in width, and thus are three-dimensional. Allen (1970) and many others observed that grain flows in wide flumes and on subaerial dunes have a lobate form, often with coarse grains at the leading edge. Furthermore, Allen (1970, 1984) and others observed that grain flows do not cover the whole lee side in one sweep, but tend to deposit at some point on the slope, to be activated again when pushed by an adjacent grain flow. This probably has the effect that the vertical sorting in the cross-stratification is less well developed than predicted by the one-dimensional segregation models of Makse and Koeppe and coworkers.

There are indications (Hunter and Kocurek, 1986) that the frequency of grain flows is to some extent affected by the turbulent vortex shedding of flow at the brink point of dunes, superimposed bedforms on the dune, and lee-eddy impingement on the lower slip face (from the counterflow). Although there is no data at all to assess the importance of these phenomena for grain flow frequency (and therefore grain flow thickness), it is assumed here that these effects are of secondary importance only.

Concluding, the size of the wedge of sediment that is deposited at the top of the lee slope determines the dynamics and size of the grain flows in sands and gravelly sands. Thus the cross-strata thickness is dependent on the volume of the wedge and therefore on the dilatation angle. As a secondary effect, the grain flows are limited in width and do not only push coarse sediment downslope but also to the sides. The sorting processes in a grain flow are discussed in the next section.

6.2. Sediment sorting within grain flows

Within the grain flow, the large grains are worked upwards to the surface of the flow. As a result, these large grains have more opportunity to reach the lower foreset slope to yield net vertical fining upward sorting in dunes. The first question is therefore how the sorting within a grain flow takes place. Two hypotheses of sorting mechanisms within grain flows on the lee slope will be discussed: (1) dispersive stress and (2) kinematic sorting or percolation (see Fig. 7C). Both mechanisms yield a reverse perpendicular sorting in the grain flow due to which the large grains occur mainly in the top of the flow, allowing the overpassing mechanism to act which results in a tangential inverse sorting. In this way, the sorting in the grain flow promotes the sorting along the lee slope of the dune, and thus the vertical sorting in a dune (see Fig. 7D first panel).

1. Dispersive stress: Bagnold (1954) experimented with unimodal sediments to determine the dispersive stress in the sediment due to shearing. Viscous and inertial regimes were distinguished in parallel with laminar and turbulent flow. In the viscous regime, he found that the collision-related forces are independent of grain size, and therefore cannot cause any sediment sorting. However, the forces in the inertial regime are dependent on grain size. Bagnold argued that the larger grains of a mixture will migrate to the surface of the grain flow under influence of the dispersive pressure gradient. The result is a reverse perpendicular sorting in the cross-stratum. Furthermore, in a mixture of grains with equal size but different densities, the heaviest grains will migrate to the surface. So dispersive stress sorting is related to sediment size and density. However, Bagnold's analysis refers to well-sorted sediment, and it is not clear whether the size-dependence of forces would apply to individual grains in a poorly sorted sediment and to much thinner grain flows.

2. Kinematic sorting (Dyer, 1929, in Sallenger, 1979) and percolation are related to the relative size differences between grains. For kinematic sorting the sediment mixture must be in motion (moved, transported or shaken). As a consequence, the sediment is dilated (i.e. the pore space is increased because the colliding grains push neighboring grains away) and the small grains tend to filter down between the large grains. The effect is that the small grains move downwards and the large grains upwards, irrespective of their weight, resulting in a reverse perpendicular sorting in the cross-stratum. This mechanism can easily be demonstrated by shaking any mixture of small grains and large grains. Percolation is defined here to refer to static sediment in which the small grains are small enough to fall through the interstices of the large grains without dilation, as opposed to kinematic sorting where the sediment is in motion and dilated.

For modelling purposes, it would be necessary to determine whether kinematic sorting or dispersive stress or a combination of both is responsible for the sorting. The result of the two is the same for sediments with equal densities, which makes it difficult to distinguish between the two. The evidence concerning the dispersive stress and kinematic sorting hypotheses is conflicting. In experimental subaerial grain flows and in natural beach foreshore deposits, Sallenger (1979) found that the dispersive stress sorting was dominant, based on the behaviour of heavy minerals. Hunter (1985a) on the other hand found contrary evidence in favour of kinematic sorting, also based on heavy minerals in grain flow foresets.

Legros (2002) argued that the dispersive stress gradient necessary for reverse perpendicular sorting immediately causes expansion of the grain flow, until the dispersive stress has become equal to the hydrostatic pressure gradient. Then only lighter grains can be worked up; therefore, the larger and heavier grains tend to migrate downwards while the smaller and lighter grains migrate upwards. This means that the dispersive stress cannot be responsible for reverse perpendicular sorting. Legros also provided arguments why the conclusions of Sallenger are not substantiated by his data. As grain flows on foresets is of interest here, a reasonable working hypothesis is that sorting is dominated by kinematic sorting (not dispersive stress), following Hunter and Legros.

6.3. Sorting by grain flows rejuvenating underlying sediment

The overpassing mechanism allows the large grains to roll further downslope than the small grains in the process of individual grain rolling on the foreset slope. In the case of grain flows (with higher transport rates), an additional sorting mechanism may take place. In the experiments of Blom and Kleinhans (1999) an hitherto unrecognized sorting mechanism was visually identified by the author. It was observed that the grain flows were thinner than the largest grain diameter in the flow, which consequently protruded. This may have been amplified by kinematic sorting. The protruding grains were often dragged downslope by a next grain flow that overran the flow deposit of which the grain was a part (see Fig. 7D). This may have led to a more pronounced sorting than would have been the case for less protruding grains. Obviously, it depends on the size of the largest grains relative to the thickness of the grain flow from which the large grains protrude.

The possibility of this drag mechanism is hinted at by Tischer et al. (2001), who measured velocities of individual grains in grain flows in uniform sand (0.3–0.5 mm grain sizes) at several locations in the flow. (They claimed that they were the first who did this, but apparently they were unaware of the work by Bagnold, Allen, Makse, Kakalios and others.) They found that the upper part of a grain flow consists mostly of sliding, rolling and saltating particles. Lower on the slope, in the more mature grain flow, the movement becomes a shock wave propagating through the deformable bed, which moves faster than the individual particles. In experiments without a deformable bed, the shock wave part of the grain flow did not develop at all. Tischer et al. conclude that a necessary condition for the occurrence of grain flows is the presence of a deformable bed below that grain flow.

If grain flows indeed need a deformable bed to develop, then this has consequences for the sorting. This hypothesis is developed as follows. The deformable-bed condition means that the grain flow exerts drag on the previously immobile bed, which leads to mobilisation of the underlying material. In nonuniform sediment, this underlying material is sorted coarsening upward in the perpendicular direction (within a grain flow) due to the kinematic sorting. Therefore, it is preferentially the coarse sediment that is dragged down the slope. In addition, large grains on small grains are more affected by resistance than small grains on large grains (Makse, 1997). Thus the large grains in the deformable bed, which are on top due to the kinematic sorting, are preferentially mobilised. The drag is not transferred into the underlying sediment in a gradual way, but in a nonlinear decrease with depth, with a strong reduction or maybe even slip condition at the transition from coarse to fine sediment. This nonlinearity is obviously stronger for bimodal sediment. The result obviously is that the downslope part of the foreset becomes enriched in coarse sediment, leading to the fining-upward sorting in the whole dune. Most importantly, the deformable-bed condition thus implies that the sorting in grain flows can be a two-stage process; some of the sorting takes place in the initial grain flow, and the sorting is continued in the rejuvenation induced by the next grain flow. It can be expected that the vertical sorting is thus much more effectively attained than without this drag effect. This may also have consequences for thin debris flows, where the rejuvenation of underlying material has not yet been studied (Iverson and Vallance, 2001). The two-stage process has been confirmed in subaqueous delta-experiments with badly sorted sediment by Kleinhans (2002).

7. Additional factors affecting sorting in dunes

7.1. The effect of sediment bimodality

Sediment bimodality may play an important role. With two strictly bimodal grain species, the opportunity for percolation (without dilatation) is large. Percolation occurs best in a very bimodal mixture, for in a unimodal mixture there are also many grains of intermediate size that block the interstices. Note that three measures are necessary to describe the sediment bimodality: the difference between the grain sizes of the two modes, the sorting of each mode and the relative proportions of the two modes. For a large difference in grain size between the modes, the opportunity for percolation is large. However, with two poorly sorted, overlapping modes, the grain sizes in between the modes block the interstices and prohibit percolation. A coarse-dominated bimodal sediment causes the mixture to be open-work gravel with more opportunity for percolation, whereas a fines-dominated bimodal sediment gives a matrix-supported gravel without percolation opportunity.

Strictly bimodal sediment may lead to a perfect segregation, as was shown by Makse and coworkers. They found a perfect segregation for grains of equal shape and with a size ratio of $D_{large}/D_{small} > 1.5$. Although this was in a controlled laboratory setting, it indicates that the bimodality of the sediment may lead to a more abrupt change of sediment size in the depth of the dune than with a more unimodal sediment.

Furthermore, the different sizes may have different angularities, leading to different angles of repose and stratification tendencies. This is clearly indicated by experiments of Carling and Glaister (1987), who experimented with a very bimodal gravel and sand mixture deposited in a Gilbert-type delta in a flume. They found a clear reverse tangential sorting but no cross-stratification, and the more irregular shaped grains at the top of the slip face. Furthermore, the sand percolated into the gravel on the top of the delta, which means that the kinematic sorting already happens without movement of the gravel. Carling and Glaister (1987) argued that the percolation of sand would have been even stronger if the gravel species had been more rounded and uniform.

Shaw and Gorrell (1991) described the sediment sorting of extremely bimodal sediment in subaqueous bedforms formed below a glacier. The large grain size was 64 mm while the small grain size was 0.125 mm. They found a clear reverse perpendicular sorting in the cross-stratification, but no tangential sorting. The lower part of the cross-strata commonly had more small grains as matrix infilling, while the upper part of the strata had less matrix and sometimes were open-worked gravels. Shaw and Gorrell attempted to explain the strong perpendicular sorting with variations in sediment supply due to the migration of bed load sheets, but did not offer any proof. It is likely that percolation alone can explain the perpendicular sorting in their case.

Extreme results were reported by Thomas in highly controlled laboratory experiments. When the size ratio between the two species of an extremely bimodal mixture became larger than 5, kinematic sorting with large grains on top of the small no longer prevailed, but the large grains moved to intermediate levels in the grain flows. This was apparent in various settings (piles, chutes and rotating cylinders). Apparently, the high mass of the large grains pulling these down into the grain flow started to dominate the geometric effects of kinematic sorting and percolation. In nature these conditions probably are rare because with such large size ratios the smaller grains are likely in suspension already if the larger become involved in grain flows at the lee side of bedforms.

Lecocq and Vandewalle (2000) did highly controlled laboratory experiments with bimodal and trimodal mixtures in air, and found that the trimodal mixture exhibited more complex stratification and sorting patterns than the bimodal, which was related to more variations of the angle of repose for different combinations of three grain species than for two, and to the overpassing by bouncing grains on the slope. Their experiments indicate that the sorting mechanisms are usually more complex for trimodal or possibly badly sorted unimodal sediment than for strictly bimodal mixtures used by other physicists.

Concluding, both the reverse perpendicular and tangential sorting are more efficient in more bimodal sediment with more or less equal amounts of sediment in both modes. When one of the modes is very dominant, the sorting mechanism tends to the behaviour of unimodal sediment. The vertical change of grain size in the dune is more abrupt than for unimodal sediment.

7.2. Counterflow effects on the foreset and bottomset deposits

Termes (1986) suggested that the downward movement of grains is somewhat counteracted by the counterflow in the lee of the dune or delta. Also Carling and Glaister (1987) observed a decreased downslope dip of asymmetric grains on the lee slope, which they attributed to the counterflow. However, the counterflow acts on the grains as a function of their area, say, $\sim D^2$, while gravity in the settling motion acts on the weight, say, $\sim D^3$. This suggests that the momentum gained by a large falling grains is relatively more important than the counterflow, and modification of the grain flow by the counterflow is at best a secondary effect. The dip angle of the settled grains on the lee slope might be changed but re-entrainment by the counterflow is highly unlikely due to the high slope angle and large weight. The effect of the counterflow on the vertical sorting of large grains is therefore considered to be of secondary importance.

Suspended sediment that is captured in the counterflow, either may be deposited upstream of the reattachment zone or on the toe of the lee slope. Many authors found an enrichment of the lower parts only of gravelly cross-strata by fine sediment, which suggests a counterflow origin, e.g. Termes (1986), Love et al. (1987), and Shaw and Gorrell (1991). Turbulence in the wake of wind dunes was also found to affect the paths of falling grains (Nickling et al., 2002).

However, in the case of gravel dunes, the flow strength is relatively large; otherwise, the gravel would not be transported in the dune phase. Since the gravel dunes are relatively lower than sand dunes due to their larger grain size, the lee zone is smaller and the turbulence in the gravel dune trough is much stronger than in sand dunes with the same height. Consequently, any fine sediment in the trough of a gravel dune is likely to be resuspended, unless it is trapped in the interstices of the gravel in the foreset. The latter probably happened in the cases described by Termes (1986), Love et al. (1987), and Shaw and Gorrell (1991). Nevertheless, bottomsets have been found downstream of gravel bedforms, suggesting that it is not impossible. Carling and Glaister (1987) found counterflow ripples at the lee side of their laboratory gravel bar. The effect was matrix infilling by sand of the lower part of the gravel cross-strata.

Depending on the suspended sediment concentration in the counterflow and the strength of the counterflow, the effect of bottomsets on vertical sorting in the river bed is more important in sandier sediments. Hunter (1985a) found that the cross-strata in sandy dunes showed reverse perpendicular sorting halfway down the lee slope, but normal perpendicular sorting at the toe. This can probably explained with continuous deposition of suspended sediment on the toe. Due to sorting in the grain flow, the largest grains end at the toe, but afterwards are buried below a relatively thick toeset from suspended sediment. The result is a normal perpendicular sorting.

Jopling (1965) and Allen (1963) studied the effect of suspended sediment deposition on the toe of the lee slope on the shape of the cross-strata. Both authors found that the contact between cross-strata and the lower bed is angular when little or no sediment is deposited from suspension, while the contact becomes increasingly tangential when more sediment is deposited from suspension.

Allen (1963, 1970) attributed the lack of sorting in his experiment with the highest flow velocity (see section on experimental data) to the continuous grain flowing. The frequency of grain flowing was so large that grain flows were overrunning each other which prevented effective sorting. It is important to note that some experiments of Hunter and Kocurek (1986) had the condition of continuous grain flowing as described by Allen. In this condition, the slope of the foreset was significantly lower than with a lower frequency of grain flows. This suggests an alternative to Allen's interpretation of overrunning grain flows. The grain fall deposition from suspension may have become so intense that the wedge was buried before it exceeded the critical slope for failure. Or maybe the wedge failed and created a grain flow, but this grain flow only overran but did not rework the thick grain fall deposit. The effect would be that the grain flow deposit is coarsening in the downslope direction, but the grain fall deposit (with the largest grains settling on the upper foreset) is fining in the downslope direction. Thus there is no net sorting within the dune or delta because the two sorting mechanisms oppose each other.

With his model, Hunter (1985b) was able to explain that the grain flows in water are much more frequent than in air, and therefore the ratio of grain flow deposits to grain fall deposits on foresets (see Fig. 4) is much larger in water than in air. So in subaqueous dunes, the cross-stratification generally consists of grain flow deposits only, whereas in air the cross-stratification may consist of couplets of grain fall and grain flow deposits (Hunter, 1985b; Nickling et al., 2002). Allen (1963) forced a certain combination of dune height and flow velocity in his experiments, and it could be that his conditions were such that both grain fall and flow deposits were preserved in his deposit, leading to the disappearance of the net fining upward sorting. Regardless the truth in that case, it seems to be important to have combinations of flow velocities, sediment transport and dune heights that occur in natural conditions as well.

With very large suspended sediment concentrations in the counterflow, enough sediment may accumulate in the lee zone for the formation of counterflow ripples. Of course the counterflow must be strong enough to form the ripples, although not so strong as to induce much resuspension. Boersma et al. (1968) found thick sandy bottomsets below cross-stratified deposits of straight crested dunes in gravelly sand. Boersma et al. were able to identify climbing counterflow ripples and wavy lamination from the counterflow, irregular foresets from the reattachment zone, and coflow ripples from downstream of the reattachment zone. A reconstruction of the setting revealed that the sediment was probably deposited on a high part of the point bar, at which the flow velocity rapidly decreased and large concentrations of sediment were deposited. This explains why the coflow ripples and irregular reattachment ripples were also preserved.

Lower in the deposits, no sandy bottomsets were found. These findings probably represent a special case which is not very important for foreset deposits in channel beds from dunes.

Concluding, depending on the suspended sediment concentration, the lower part of cross-strata are enriched with fine sediment. Furthermore, a bottomset of fine sediment may be preserved, if the turbulence in the dune trough is not so strong that it is immediately resuspended (which is more likely in gravel dunes). The effect on the vertical sorting in dunes is a zone of decreased upward fining or even upward coarsening in the lowest part of the dune. It can be expected that in very wide mixtures, these effects are significant, because when these sediments are in the dune phase, the finer fractions will be in suspension. In addition, in wind-blown deposits and special cases of alluvial deposits, grain fall deposits may be preserved in the foresets and form couplets with the grain flow deposits.

7.3. The effect of sediment transport magnitude at the brink point

According to Allen (1963, 1970), the size of the wedge of sediment that is deposited at the top of the lee slope mainly determines the size of the grain flows. Thus the cross-strata thickness is dependent on the volume of the wedge and therefore the dilatation angle. The dilatation angle is more or less constant for a certain sediment mixture in water, and is in the order of 5–10°. However, the mass of sediment in the wedge depends on the flow at the brink point. The horizontal path length of sediment that starts to fall out of the flow at the brink point, depends on the flow velocity as well as the settling velocity of the grains. Thus large grains (which have a large settling velocity) are dropped at the top of the lee slope while smaller grains deposit further downstream. In a larger flow velocity, the sediment is smeared out over a larger distance because the water and suspended sediment need a longer run-out path before the velocity is reduced to the point of settling. The effect is that the wedge of sediment also becomes longer, and contains more sediment and therefore the grain flow will be larger. The larger flow velocity also causes the sediment transport to be larger, which counteracts the smearing out of the sediment over a longer wedge. Consequently, the frequency of grain flowing need not become smaller when the flow velocity is increased. Thus the grain flow thickness and the cross-strata thickness depends on the flow velocity, on which the sediment transport also depends.

The effect of very high sediment transport was studied by Allen (1963, 1970), who distinguished between discontinuous grain flowing, that occurs at low sediment transport, and continuous grain flowing, that occurs at high sediment transport. The cross-stratification disappeared with increasing (continuous) grain flow frequency. The grain fall sediment is smeared out over a longer wedge and mixed into the grain flow, so no grain fall deposit is preserved either. To a limited extent, this was also found in delta experiments (preliminary report in Kleinhans, 2002).

Also Makse and coworkers found that above a certain limit of input sediment transport, the grain flows are too fast and the kink is not able to develop and there no longer is a competition from shape segregation. The size segregation mechanism on the other hand is still effective, leading to reverse tangential sorting. In intermediate sediment transports the kink and the stratification are only weakly developed, which allows a size segregation in combination with weak stratification.

An unanswered question is how the condition of continuous grain flowing (leading to poorly developed cross-stratification) in high sediment transport is related to dune height. In the experiments for which the fading of cross-stratification was reported (Allen, 1970; Makse and coworkers; Koeppe et al., 1998; Kleinhans, 2002), the dune or delta height was artificially kept constant whereas the sediment input was increased. In nature, an increase in sediment transport probably is the result of an increase of flow velocity. This increased flow velocity may at the same time lead to higher dunes. The larger sediment transport is then distributed over a longer slip face, and thus the grain flowing need not become continuous if the adaptation of dune height is not very slow. The thickness and frequency of the grain flow thus depends on the flow velocity near the dune top, the sediment transport and the dilatation angle of the mixture. Alternatively, in the very extreme flows and sediment input at which the stratification would disappear according to Allen and Makse, the dunes may have been washed out already.

Hunter and Kocurek (1986) collected data on grain flow dynamics in uniform sand which may provide preliminary answers. They found that the grain flow thickness (or laminae thickness) were independent of the grain flow frequency (see Fig. 9a), which can be interpreted as independence from the migration celerity of the slip face and the sediment transport rate. This agrees with the idea that the foreset process is largely independent of the flow and sediment transport condition upstream of the brink point, but depends on the behaviour of the wedge on the upper foreset slope. Interestingly, Hunter and Kocurek found that the thickness of the grain flows is dependent on the height of the bedform (see Fig. 9b). In Fig. 9, symbols denote the bedform type on top of the delta in the flume experiments. It can be seen that there is no obvious trend of bedform type with increasing delta height or laminae thickness, which again suggests that the grain flow magnitude is independent of conditions upstream of the brink point. The conclusion from this set of experiments must be that the sediment volume in the wedge somehow depends on the height of the delta. The larger the delta height, the larger the sediment wedge and therefore the thicker the laminae. This was confirmed with field data of wind dunes by Nickling et al. (2002). A hypothetical explanation is that the flow velocity over higher dunes is larger, leading to higher velocities of the grains downstream of the brink point and therefore a longer and larger sediment wedge on the upper foreset slope, leading to larger grain flows. For the experiments, however, the dune height is not dependent on the flow but is a priori determined by the experimenter. The water depth above the delta is far too small for dunes of that height. Therefore, these experiments cannot be used to determine the relation between flow velocity above the delta and wedge size (or laminae thickness).

Concluding, there is a rough relation between dune height, sediment transport and the frequency of grain flows, but there is no suitable data to determine the relations. Since both dune height and sediment transport are related to the (water) flow conditions, it is hypothesized that the effectiveness of sorting mechanisms decreases with increasing flow strength.

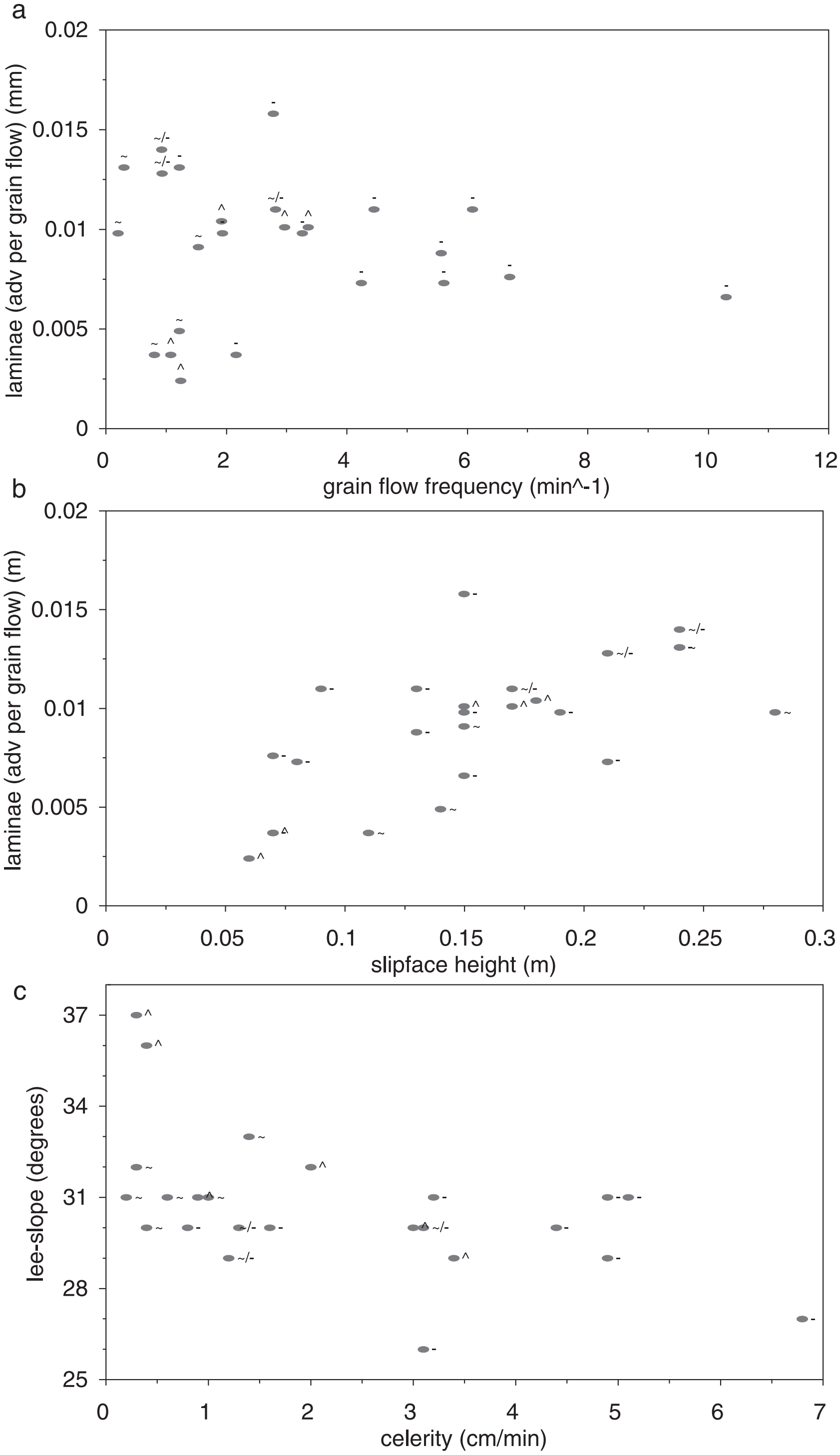
7.4. Armouring and bottomsets

Sorting of sediment that is in transport in the bed load phase depends on the relative mobility of the different grain sizes. Small grains may already be in transport, while the larger are immobile or less mobile. This may lead to an enrichment of the bed surface of large grains, which is called armouring. An armour layer is essentially an erosional feature, and it is assumed that an armour layer is not formed simultaneously with a bottomset consisting of fine sediment deposited from suspension. At the same time, it is reasonable to assume that kinematic sorting also takes place in the traction carpet. An armour layer on dunes was found by Love et al. (1987) and in Blom and Kleinhans (1999) (see Figs. 5 and 6).

The prediction of incipient motion of sediment has been the topic of extensive research. Obviously, the critical shear stress is larger for larger grains. However, grains in a bed of mixed grain sizes experience a shear stress that is related to their position relative to the other grains. Large grains may protrude above the bed and thus be more exposed to the flow. As a consequence, they become entrained at a lower shear stress than it would have on a bed of uniform grain size. Small grains may hide in the wake of large grains and become entrained at a higher shear stress than in the uniform sediment case. Wilcock (1993) and Kleinhans and Van Rijn (2002) show that unimodal sediment mixtures tend to show near equal mobility of large and small grains, whereas in bimodal sediment mixtures, the two modes are increasingly independent, tending to the mobility related to uniform sediment of each mode separately.

Concluding, for unimodal but nonuniform sediments, the size selection is small as well as the range of bed shear stresses in which the larger grains are immobile or partially mobile while the smaller grains are already in transport. For bimodal sediment, the size selection becomes increasingly important for increasing difference in grain size of the two modes in the grain size distribution. Consequently, armouring becomes more likely with increasing differences in grain size, that is, stronger bimodality.

Furthermore, deposition of a bottomset is unlikely when the bed is armouring at the same time. When the


a
laminae (adv per grain flow) (mm)
grain flow frequency (min^-1)
b
laminae (adv per grain flow) (m)
slipface height (m)
c
lee-slope (degrees)
celerity (cm/min)

armour layer in the dune troughs is being depleted of transportable grains, those grain sizes above the threshold for suspension will be entrained and not deposited.

8. Synthesis: processes and variables

8.1. Primary controls on grain fall, individual grains rolling and grain flows

The characteristics of the sediment mixture (grain size, standard deviation of the mixture, and angularity of the different grain size fractions) are the primary controls on the processes. For almost uniform sediment, there is not much to be sorted, whereas widely nonuniform mixtures may show strong sorting. The bimodality of the sediment determines the kinematic sorting and percolation effectiveness.

The flow and therefore the mobility of the sediment is important in only three aspects:

1. suspension and therefore the grain fall process from the sediment-laden flow downstream of the brink point depends on the ratio of (shear) velocity and settling velocity of each size fraction. Especially in the case of bimodal sediment, this ratio also determines which size fractions may settle at all on the foreset or in the trough, and which remain in full suspension,
2. the flow and sediment mobility determine the height of dunes and thus the length of the foresets along which the sediment is sorted, and
3. the volume of the wedge of sediment forming at the upper foreset slope may depend on the flow velocity above the dune top, roughly leading to larger wedges for higher dunes.

The resulting deposit is a sediment wedge with a downslope decrease in thickness following the exponential or power function of deposition from suspension with distance from the brink point. The counterflow at the lee side of the foreset slope may induce secondary effects like suspended sediment deposition on the lower foreset slope and skewing the dipping angles of larger grains on the foreset.

The sediment wedge fails when its angle (at some point, usually the upper) becomes larger than the static angle of repose. Both individual grain movement and grain flows on the foreset slope are initiated by this failure. The sediment wedge volume, grain flow thickness, and laminae thickness seem to be dependent on the dune height.

The individual grain movement is governed by the static angles of repose of the individual grain size fractions, and by the static angles of repose of the grain size fractions on fractions of other grain sizes. The individual grain movement may lead to stratification and to segregation of the grain size fractions. The mechanism of kinematic sorting or percolation plays a limited role in bringing the large grains to the top of the moving sediment, leading to stratification or segregation depending on the mutual angles of repose of fine and coarse sediment. Individual grain movement on foreset slopes is relevant for dunes or bars in very coarse sediment, where the ratio of grain flow thickness to grain diameter is small.

In grain flows, the condition of a mobile underlying bed is important. A two-stage process leads to net vertical sorting in a dune:

1. in an individual grain flow, kinematic sorting or percolation leads to coarsening upward in the reverse perpendicular direction. The angle of repose of large grains on small grains is relatively small; therefore, the large grains are much more unstable than the small underlying grains.
2. the next grain flow drags the underlying sediment of the previous grain flow. The drag is not transferred into the underlying sediment in a gradual way, but mainly applied to the protruding

Fig. 9. Data of Hunter and Kocurek (1986). (a) Relation between the thickness of laminae (advance of slip face per grain flow) in cross-bedding and the grain flow. No obvious trend can be found, except that the most frequent avalanching occurs in upper plane bed conditions on the delta. Symbols denote bed condition on the delta: -: upper plane bed, ~: ripples and ^: dunes (classification not defined by Hunter, but Hunter suggests to be following Simons and Richardson, 1965). (b) Relation between laminae thickness (and related grain flow thickness and wedge volume) and delta height. Hunter and Kocurek (1986) give a rough relation as thickness = 0.060 times the delta height. (c) Relation between the slope of the foreset with the celerity of the dune (migration velocity).

large grains of the previous grain flow. The result obviously is that the downslope part of the foreset becomes enriched in coarse sediment, leading to the fining-upward sorting in the whole dune.

Summarizing, the following variables seem to be the most important for the vertical sorting in dunes:

- sorting (standard deviation) of the sediment mixture delivered to the brink point,
- height of the dune or bar relative to the average grain size of the mixture,
- velocity of the flow above the brink point relative to the settling velocity for all grain size fractions (determining the size of the wedge and therefore the thickness of the grain flow),
- frequency of the grain flows, determined by celerity of the dune (in turn determined by sediment transport divided by dune height) and celerity of the grain flows on the foreset slope.

The frequency of grain flows can either directly be measured, or derived from the celerity of the dunes (m/s) divided by the thickness of the grain flows (m), yielding the frequency (s^{-1} = Hz).

8.2. Hypothetical explanation for difference between segregation and stratification

In the experiments of Koeppe et al. (1998), it was found that the phenomena stratification and segregation cannot occur simultaneously. Koeppe et al. seem to explain the disappearance of the stratification with increasing transport rate like Allen does with the continuous grain flowing. Makse and coworkers explain the transition from stratification to segregation with angles of repose for the two grain species (and did not investigate the effect of transport rate). All these experiments and models refer to small differences in grain sizes of strictly bimodal sediments. In nature, the sediment usually is not strictly bimodal, and continuous grain flowing is not the condition at which segregation (fining upward in the whole dune) occurs. On the contrary, in continuous grain flowing the segregation disappears. It is therefore the question whether the explanations provided by the physicists can be extended to natural conditions.

Clues as to what governs stratification or segregation in nature can be derived from the literature. There seem to be several types of cross-stratification, distinguishable with diagnostic characteristics, some of which are:

- in ripples and dunes of fine sediment, visible due to the drape of very fine sediment from suspension on the whole foreset,
- in dunes of fine sediment, visible due to the couplets of grain flow and grain fall deposits,
- in ripples and dunes, visible due to the reverse perpendicular sorting caused by kinematic sorting,
- in dunes and bars of mixed coarse sediment, visible due to relicts of kinematic sorting,
- in dunes and bars of mixed coarse sediment, visible due to the direction of dipping (asymmetric) grains, and
- in dunes and bars of mixed coarse sediment, visible due to variations of mixture composition between the different laminae.

The point is that a certain deposit may be recognized as a cross-stratificated unit but does not necessarily have the same origin as the stratification sensu Makse and Koeppe and coworkers, who call the latter three types of 'cross-stratification' segregation.

A hypothesis is forwarded here of the natural conditions in which pure stratification (cross-stratification) without any segregation (fining upward trend in whole dune) sensu Makse and Koeppe and coworkers occurs. Hypothesized conditions for pure stratification could be:

1. Dunes in equilibrium with the flow, combined with much suspension of sediment in a sand bed river, in which grain fall and grain flow deposits are preserved. For such a case to happen in alluvial conditions, the settling from suspension must be extremely high, while the flow strength must not be to high to erode the dunes into upper plane bed (e.g. the Platte river, Mohrig, 1994).

2. This condition is based on the hypothesis forwarded earlier in this paper: the sorting on foresets is a two-stage process, first with kinematic sorting in a grain flow, and then drag by the second grain flow by which the coarse sediment is preferentially dragged downslope. To create true stratification, the second stage of this process should not take place. This stage

would not take place if the grain flow thickness were much larger than the size of the protruding large grains below the grain flow, and if the grain size differences in the sediment is small. It is hypothesized here that these conditions are fulfilled when the sediment volume in the wedge is large (therefore in high dunes, e.g. in the IJssel), while the sediment is relatively fine (sand) and not too poorly sorted (ratio of dune height over average grain size). Stratification without any segregation would thus occur in moderately sorted sandy sediment with high dunes.

8.3. Conceptual model

Based on this review and the sparse sorting data, a conjecture of vertical sorting in various conditions is given in Fig. 10. For simplification, each sediment mixture is simply divided into two grain size fractions with about an equal percentage of sediment in each class. The vertical distribution of the larger grain size fraction in the dune is given qualitatively in Fig. 10, to indicate the form of the vertical sorting curve. On the vertical axis the height above the base of the dune is given, and on the horizontal axis the fraction in the larger grain size fraction is given. For example, the sorting in a dune consisting of sand and gravel is given as a gravel fraction or percentage as a function of depth below the dune top. The slope of the lines indicates the strength of the upward fining trend. The essential elements of the vertical sorting curves are related to the different types of deposits: foreset and bottomset deposits, as well as armouring in a topset (see Fig. 10).

The ideas behind the columns in the conceptual model are primary factors determining the sorting efficiency. These are: for highly nonuniform sedi-

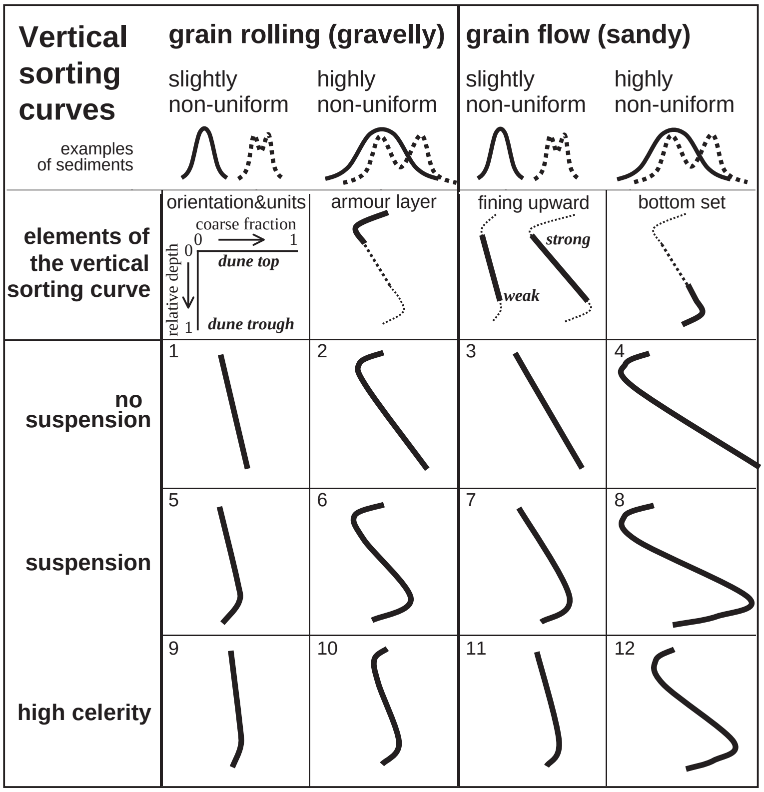


Fig. 10. Conceptual model of sorting as a function of the most important variables. The curves denote the abundance of the coarse sediment at different heights in the bedforms. A vertical line means no significant upward fining, whereas a low-sloping line means a strong fining upward trend. See text for explanation.

ment the sorting is better developed than near-uniform sediment, for grain flows the sorting is better developed than for individual grain rolling due to the drag effect, and grain flows are more often expected in sandier sediment than in coarse gravel. Gravelly armour layers may be expected on dunes in highly nonuniform sediment. The ideas behind the rows in the model are that suspension of finer fractions enriches the lower foreset, and with higher dune celerity the sorting efficiency becomes less large, while the effects of suspension obviously remain important. A number of secondary effects and bimodality of the sediment have not been included. The model does not include the (maybe rare) case of high dune celerity without significant suspension of sediment.

The cells of Fig. 10 have been numbered for quick reference. The data sets can be compared to this conjectured curves as follows. The Rio Grande channel data (Love et al., 1987) fits in cells 2 or 4, or 6 or 8 if the bottomset deposition is taken into account. The IJssel data (Dillingh, 1990) fits in cell 3 or 7, depending on the interpretation of the flow conditions. The laboratory conditions of Ribberink (1987), Kleinhans (2002) and Blom et al. (2000) probably fit in cell 4, whereas the Termes (1986) data fits in either cells 4 and 8. The case described by Boersma et al. (1968) is an extreme case of cell 8. The relict gravel dunes described by Carling (1996) and by Shaw and Gorrell (1991) should probably be classified in cell 6. All the Makse and Koeppe experiments belong in cell 1. The Allen experiments finally belong in cells 7 and 11.

9. Concluding remarks

This review was limited to a qualitative analysis of the sparse available data of vertical sorting in dunes, and a discussion of the possible sorting mechanisms in a large number of settings from models of grain behaviour in air to sand and gravel dunes in laboratory flumes and rivers to relict dunes of extreme floods. The following factors seem to be the most important for the vertical sorting in dunes:

1. sorting (standard deviation, skewness and bimodality) of the sediment mixture delivered to the brink point,
2. height of the dune or bar relative to the average grain size of the mixture,
3. velocity, or Shields sediment mobility, of the flow above the brink point relative to the settling velocity for all grain size fractions,
4. frequency of the grain flows, determined by celerity of the dune (in turn determined by sediment transport divided by dune height) and celerity of the grain flows on the foreset slope.

The sorting at the lee side of dunes is not entirely independent of the general flow conditions because of the role of settling from suspension. This is specifically important in conditions with significant suspension and wide mixtures, where finer grains are fully suspended while large grains are only incipiently mobile.

Although the vertical sorting is relevant for sediment transport models, no quantitative model has been developed that is generally applicable to the alluvial setting. Neither are experimental data available with systematic variation in a range of relevant factors and conditions. The obvious next step is to do those experiments and to develop a physical model for the vertical sorting in natural conditions. A logical set-up for such a set of experiments would be to build laboratory Gilbert-type deltas in a narrow flume with different sediments, heights and celerities (determined with input sediment transport), whereby the flow is adapted such that the sediment feed can be transported at the same energy slope for all experiments. The deltas can be recorded on film for grain flow dynamics analysis and can be sampled in layers to quantify the upward fining trend. A preliminary report of such experiments, confirming the importance of factors 1 and 3, is found in Kleinhans (2002). Finally, the transition from stratification to segregation, and the different types of stratification, should be studied further in natural deposits and flume experiments.

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References

Allen, J.R.L., 1963. Sedimentation to the lee of small underwater sand waves: an experimental study. Journal of Geology 73, 95–116.

Allen, J.R.L., 1970. The avalanching of granular solids on dune and similar slopes. Journal of Geology 78, 326–351.

Allen, J.R.L., 1984. Sedimentary structures, their character and physical basis. Developments in Sedimentology, vol. 30. Elsevier, Amsterdam.

Bagnold, R.A., 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Royal Society of London, Proceedings Series A (225), 49–63.

Bak, P., Tang, C., Wiesenfeld, K., 1988. Self-organized criticality. Physical Review A, 364–374 (July 1).

Bennett, S.J., Best, J.L., 1995. Mean flow and turbulence structure over fixed, two-dimensional dunes: implications for sediment transport and bedform stability. Sedimentology 42, 491–513.

Blom, A., Kleinhans, M.G., 1999. Non-uniform sediment in morphological equilibrium situations. Data Report Sand Flume Experiments 97/98. University of Twente, Rijkswaterstaat RIZA, WL/Delft Hydraulics. University of Twente, Civil Engineering and Management, The Netherlands.

Blom, A., Ribberink, J.S., Van der Scheer, P., 2000. Sediment transport in flume experiments with a trimodal sediment mixture. In: Nolan, T., Thorne, C. (Eds.), Proc. Gravel Bed Rivers Conference 2000, 28 August–3 September, New Zealand. Special public. CD-rom of the New Zealand Hydrological Society.

Blom, A., Ribberink, J.S., de Vriend, H.J., 2003. Vertical sorting in bed forms: flume experiments with a natural and a trimodal sediment mixture. Water Resour. Res. 39 (2), 1025, doi:10.1029/2001WR001088.

Boersma, J.R., Van de Meene, E.A., Tjalsma, R.C., 1968. Intricated cross-stratification due to interaction of a mega ripple with its lee-side system of backflow ripples (upper-pointbar deposits, Lower Rhine). Sedimentology 11, 147–162.

Boutreux, T., 1998. Surface flows of granular mixtures: II. Segregation with grains of different size. European Physical Journal. B 6, 419–424.

Boutreux, T., Makse, H.A., De Gennes, P.G., 1998. Surface flows of granular mixtures: III. Canonical model. European Physical Journal. B 9, 105–115.

Carling, P.A., 1996. Morphology, sedimentology and palaeohydraulic significance of large gravel dunes, Altai Mountains, Siberia. Sedimentology 43, 647–664.

Carling, P.A., Glaister, M.S., 1987. Rapid deposition of sand and gravel mixtures downstream of a negative step: the role of matrix-infilling and particle-overpassing in the process of bar-front accretion. Journal of the Geological Society (London) 144, 543–551.

Cizeau, P., Makse, H.A., Stanley, H.E., 1999. Mechanisms of granular spontaneous stratification and segregation in two-dimensional silos. Physical Review E, 59.

Dillingh, D.A., 1990. Transport layer sampling in the river IJssel near Deventer, The Netherlands (in Dutch). Soil Mechanics Laboratory Delft, Delft, report number CO318420, The Netherlands.

Druitt, T.H., 1995. Settling behaviour of concentrated dispersions and some volcanological applications. Journal of Volcanology and Geothermal Research 65, 27–39.

Friedman, G.M., 1979. Address of the retiring president of the International Association of Sedimentologists: differences in size distributions of populations of particles among sands of various origins. Sedimentology 26, 3–32.

Hunter, R.E., 1985a. Subaqueous sand-flow cross-strata. Journal of Sedimentary Petrology 55, 886–894.

Hunter, R.E., 1985b. A kinematic model for the structure of lee-side deposits. Sedimentology 32, 409–422.

Hunter, R.E., Kocurek, G., 1986. An experimental study of subaqueous slipface deposition. Journal of Sedimentary Petrology 56, 387–394.

Iverson, R.M., Vallance, J.W., 2001. New views of granular mass flows. Geology 29, 115–118.

Jopling, A.V., 1965. Laboratory study of the distribution of grain sizes in cross-bedded deposits. In: Middleton, G.V. (Ed.), Primary Sedimentary Structures and their Hydrodynamic Interpretation, Spec. Publ. No. 12. Soc. of Econ. Paleontologists and Mineralogists, Oklahoma, USA, pp. 53–65.

Klaassen, G.J., 1987. Experiments on the effect of gradation on sediment transport. Euromech 215 Colloquiem, Genova, Italy, September 15–19, also Delft Hydraulics Publication 394, Delft, The Netherlands.

Klaassen, G.J., 1991. Experiments on the effect of gradation and vertical sorting on sediment transport phenomena in the dune phase. Grain Sorting Seminar, 21–25 October, 1991, Ascona (Switzerland). Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der Eidgenössischen Technischen Hochschule Zürich, pp. 127–146.

Klaassen, G.J., Ribberink, J.S., De Ruiter, J.C.C., 1987. On the transport of mixtures in the dune phase. Euromech 215 Colloquiem, Genova, Italy, September 15–19, also Delft Hydraulics Publication 394, Delft, The Netherlands.

Kleinhans, M.G., 2001. The key role of fluvial dunes in transport

and deposition of sand–gravel mixtures, a preliminary note. Sedimentary Geology 143, 7–13.
Kleinhans, M.G., 2002. Sorting out sand and gravel; sediment transport and deposition in sand–gravel bed rivers. Netherlands Geographical Studies Royal Dutch Geographical Society, Utrecht, The Netherlands, p. 293.
Kleinhans, M.G., Van Rijn, L.C., 2002. Stochastic prediction of sediment transport in sand–gravel bed rivers. Journal of Hydraulic Engineering 128, 412–425.
Koeppe, J.P., Enz, M., Kakalios, J., 1998. Phase diagram for avalanche stratification of granular media. Physical Review E, 58.
Lecocq, N., Vandewalle, N., 2000. Stripes ordering in self-stratification experiments of binary and ternary granular mixtures. Physical Review E 62, 8241–8244.
Legros, F., 2002. Can dispersive pressure cause inverse grading in grain flows? Journal of Sedimentary Research 72, 166–170.
Love, D.W., Gutjahr, A., Robinson-Cook, S., 1987. Location-dependent sediment sorting in bedforms under waning flow in the Rio Grande, Central New Mexico. In: Ethridge, F.G., Flores, R.M., Harvey, M.D. (Eds.), The Society of Economic Paleontologists and Mineralogists, Spec. Publ. No. 39. Recent Developments in Fluvial Sedimentology, pp. 37–47.
Lowe, D.R., 1976. Grain flow and grain flow deposits. The Society of Economic Paleontologists and Mineralogists.
Makse, H.A., 1997. Stratification instability in granular flows. Physical Review E 56, 7008–7016.
Makse, H.A., Herrmann, H.J., 1998. Microscopic model for granular stratification and segregation. Europhysics Letters 43, 1–6.
Makse, H.A., Havlin, S., King, P.R., Stanley, H.E., 1997a. Spontaneous stratification in granular mixtures. Nature 386, 379–381.
Makse, H.A., Cizeau, P., Stanley, H.E., 1997b. Possible stratification mechanism in granular mixtures. Physical Review Letters 78, 3298–3301.
Makse, H.A., Ball, R.C., Stanley, H.E., Warr, S., 1998. Dynamics of granular stratification. Physical Review E 58, 3357–3368.
McLean, S.R., Wolfe, S.R., Nelson, J.M., 1999. Predicting boundary shear stress and sediment transport over bedforms. Journal of Hydraulic Engineering 125, 725–736.
Mohrig, D.C., 1994. Spatial evolution of dunes in a sandy river. Unpublished PhD thesis. University of Washington, Washington, USA.
Nemec, W., 1990. Aspects of sediment movement on steep delta slopes. Special Publication of the International Association of Sedimentologists 10, 29–73.
Nemec, W., Postma, G., 1993. Quaternary alluvial fans in southwestern Crete: sedimentation processes and geomorphic evolution. Special Publication of the International Association of Sedimentologists 17, 235–276.
Nickling, W.G., McKenna Neuman, C., Lancaster, N., 2002. Grainfall processes in the lee of transverse dunes, Silver Peak, Nevada. Sedimentology 49, 191–209.
Postma, G., 1986. Classification for sediment gravity-flow deposits based on flow conditions during sedimentation. Geology 14, 291–294.
Powell, D.M., 1998. Patterns and processes of sediment sorting in gravel-bed rivers. Progress in Physical Geography 22, 1–32.
Ribberink, J., 1987. Mathematical modelling of one-dimensional morphological changes in rivers with non-uniform sediment. PhD thesis. Delft University, Delft, The Netherlands.
Sallenger, A.H., 1979. Inverse grading and hydraulic equivalence in grain-flow deposits. Journal of Sedimentary Petrology 49, 553–562.
Sambrook Smith, G.H., 1996. Bimodal fluvial bed sediments: origin, spatial extent and processes. Progress in Physical Geography 20, 402–417.
Shaw, J., Gorrell, G., 1991. Subglacially formed dunes with bimodal and graded gravel in the Trenton drumlin field, Ontario. Geographie Physique et Quarternaire 45, 21–34.
Simons, D.B., Richardson, E.V., 1965. A study of variables affecting flow characteristics and sediment transport in alluvial channels. Federal Inter-agency Sediment Conf. 1963. Proc., Misc. Pub. 970. US Agric., Washington, USA, pp. 193–207.
Southard, J.B., Boguchwal, A., 1990. Bed configurations in steady unidirectional water flows: Part 2. Synthesis of flume data. Journal of Sedimentary Petrology 60, 658–679.
Termes, A.P.P., 1986. Vertical composition of sediment in a dune. Report R657-XXX, Delft Hydraulics, Delft, The Netherlands.
Thomas, N., 2000. Reverse and intermediate segregation of large beads in dry granular media. Physical Review E 62, 961–974.
Tischer, M., Bursik, M.I., Pitman, E.B., 2001. Kinematics of sand avalanches using particle-image velocimetry. Journal of Sedimentary Research 71, 355–364.
Van Rijn, L.C., 1993. Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas. Oldemarkt: Aqua Publications, The Netherlands.
Wilcock, P.R., 1993. Critical shear stress of natural sediments. Journal of Hydraulic Engineering 119, 491–505.

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