

# Experimental dune trough scour in sediment mixtures

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## Abstract

Understanding causes of dune irregularity, especially dune trough scour, is important for modelling vertical sorting of sediment mixtures. Why dunes become more irregular and develop deep scour holes is only partially understood. In certain sediment mixtures, erosion-resistant coarse layers may form that decrease or inhibit dune trough scour. The causes of dune irregularity and the feedback by coarse sediment are explored in experiments and literature and are demonstrated to be related partly to the experimental setup (sediment feeding or recirculating).

## 1. Introduction

Morphological modelling of channel beds with sediment mixtures has made strong progress in the past decennium. To model the sediment transport process and the exchange between transported and bed sediment mixtures in rivers with dunes correctly, the bed level variations due to migrating dunes must be accounted for (Ribberink 1987, Paola & Borgman 1991, Parker et al. 2000, Leclair & Bridge 2001) as well as the vertical sediment sorting in the dunes (Parker et al. 2000, Kleinans 2001, 2002). Both the bed level variation and sediment sorting must be implemented in model concepts (Parker et al. 2000, Blom 2003), but are not yet predictable for various flow conditions and sediments.

Following the definition of Costello & Southard (1981), regular dunes are also called two-dimensional (2D) and the irregular three-dimensional (3D). This can be quantified in the vertical direction expressed as a probability distribution of trough depths or a probability distribution of bed level variations, and in the horizontal direction expressed as the sinuosity of the dune crest lines and connectivity (length) between crest lines.

Dunes in uniform sediment become more irregular in horizontal and vertical directions with increasing flow velocity or shear stress (Boothroyd & Hubbard 1975, Costello & Southard 1981, Terwindt & Brouwer 1986). When dunes have a highly variable trough scour depth, the deposits (sets) of the dunes are highly variable in thickness (Harms & Fahnstock 1965, Reineck & Singh 1973, Leclair and Bridge 2001). Since vertical sediment sorting is generated within a set (Kleinans 2002), set thickness variability decreases the net vertical sorting in the bed averaged over several dune lengths and set lengths.

For dunes in sediment mixtures, two complicating factors are known. First, lower mobility or immobility of the coarser sediment leads to armouring, which in turn leads to sediment supply-limited conditions. This means that the amount of mobile sediment above the armour layer is limited and insufficient to build dunes up to their equilibrium dimensions for the given flow. Instead, flow parallel sand ribbons or barchan dunes develop. Barchan dunes are highly 3D in the horizontal direction but trough scour is inhibited by the armour layer (Kleinans et al. 2002).

Second, during high discharge when large dunes form, coarse sediment concentrates in the troughs of the dunes. If this coarse lag layer is strong or thick enough, a situation comparable to armouring might develop. The lag layer just below the active dunes hinders dune growth and sediment entrainment from the bed below the active dunes (Klaassen 1991), and inhibits the formation of deep scour holes that are characteristic for irregular dunes (Hooke 1968, Van der Zwaard 1974). Also Leclair and Blom (in press) found that the trough scour depth variation, which determines lag layer formation and thus vertical sorting, is itself strongly coupled to vertical sediment sorting.

The sediment mobility differences between grain size fractions are commonly expressed as a hiding-exposure function, relating to the hiding of small grains in the lee of large grains and the exposure of large grains to the flow. A common condition in unimodal sediments is equal mobility, in which the sediment composition of bedload (temporarily 'stored' in dunes) and sediment underlying the surface sediment are equal. Bimodal sediments commonly exhibit smaller mobility of the coarser sediment.

This leads to the following hypothesis: the nature of the sediment supplied from upstream controls the mobility differences between grain size fractions and therefore affects dune irregularity. Note, in addition, that formation of a coarse layer just below the dune troughs is in effect a mobility decrease of this coarse sediment, which is then expressed in the same hiding-exposure function. In short, the mobility differences between grain size fractions strongly affect the lag layer development, and the mobility differences in turn are determined by the upstream sediment supply. Since the upstream sediment supply is different in sediment feed and recirculation flumes, the evidence from such experiments must be compared with care.

The aim of this paper is to discuss the relations between dune irregularity, upstream sediment supply and coarse sediment layer formation in two fundamentally different experimental setups: sediment feed with equal mobility and sediment recirculation with higher mobility of finer sediment. First, the methodology and setup of the experiments are given, and the results are described. Next, the controls on dune irregularity are compared for uniform and graded sediment. Then, the most important control on gravel lag formation, the mobility of the coarsest sediment, is related to the hiding-exposure phenomenon and to the experimental setting. Finally the feedback by coarse sediment layer formation on dune irregularity are discussed.

## 2. Methods

### 2.1 Methodology

The difference between two types of experiments is employed to contrast two cases: one with equal mobility and one with higher mobility of finer sediment. The tendency to form coarse (lag) layers just below dune troughs is related to the mobility of the coarse sediment. In experiments the mobility depends on dimensionless shear stress (equation) and on the upstream sediment supply boundary condition (Parker and Wilcock 1993). Consequently, there is an important difference between sediment feed and sediment recirculation flumes. In both flumes, the discharge, water depth and the initial slope are specified (and uniform flow can be maintained). In the sediment feed flume, the rate and composition of the sediment entering the flume is specified, while in the recirculating flume, it is determined by the selective transport process; thus the transport rate and composition is a dependent parameter. As a result the recirculating flume has an additional degree of freedom.

The effect of this difference is best illustrated for a case with the same initial combination of slope, discharge and water depth and sediment mixture properties. Starting with a fully mixed bed and a relatively low shear stress, in a recirculating flume only the finer sediment is entrained and migrates over the immobile coarse sediment. The sediment entering the flume is this same fine sediment. The result is therefore fine mobile sediment (possibly barchan dunes) migrating over immobile coarse gravel (lag deposit), which is a strong deviation from equal mobility. In a feed flume the coarse fractions in the feed sediment cannot be transported and therefore are deposited in the upstream part of the flume. This leads to an increase in bed slope (and, maintaining uniform flow, also water surface slope), and consequently to an increase of the bed shear stress, until the coarser sediment is transported as well. The feed system is forced (in equilibrium) to transport all the sediment that is fed in. In moderate discharge, this equal mobility condition is only attained when a mobile armour layer is formed (Parker and Klingeman 1982).

This principal difference between feed and recirculating flumes will be employed for the purpose of this paper as follows. Low and high shear stress equilibrium experiments were done in a feed flume to test whether the 2D versus 3D bedform irregularity (quantified in the vertical direction only by comparing the two tails of the probability distribution) is related to shear stress as it is in uniform sediment. The use of the feed flume ensures that no gravel lag is formed because equal mobility is enforced. Thus the effect of shear stress on dune irregularity can be isolated. A second set of experiments was done in a recirculating flume to demonstrate the effect of a gravel lag on dune irregularity and to compare this condition to one without a gravel lag. Three experiments were done on the same sediment bed: a low shear stress, a high shear stress and again the low shear stress (without remixing the bed). The recirculating flume principle enforces that lag layers are formed and history effects of vertical sorting on transport composition are allowed. Thus the effects of shear stress and vertical sorting act in combination. In addition to these experiments datasets from literature are employed from other experiments.

## 2.2 Setup of experiments in a sediment feed flume

Three feed flume experiments were done in the Tilting Bed Flume at St. Anthony Falls Laboratory, which has a length of 14 m and a width of 0.9 m (Kleinhans 2002). Equ1 was a mobile armouring experiment for reference to the plane bed condition and Equ 2 and 3 had dunes. The water depths were between 0.05 and 0.22 m, and uniform flow was maintained by adjusting the downstream weir. The test section was between 4 and 13 m from the beginning of the flume (the latter taken as just downstream of the sediment feeder). Time series of the bedlevel at a fixed point (11 m from flume entrance) and water and bed surface profiles were collected in the middle of the flume with an ultrasonic device. The flow was maintained until the system was in equilibrium, which was defined as the condition at which the variations of bedform dimensions, sediment transport and average bed level change became smaller than the measurement accuracy and variability. The bed was remixed after each experiment. It should be noted that the flume was too short to attain equilibrium of the dune height for the largest flow depth; the dune height increased towards the downstream end of the flume. The sediment was a log-normally distributed unimodal sediment, installed at a bed slope equal to that of the flume. Sediment of the same composition as the initial bed sediment was fed into the upstream end of the flume by a rising platform of 0.9 m wide and long, which rose at a constant and adjustable speed. Helley Smith measurements (ratio of nozzle exit area to entrance area 1.10, bag of 100  $\mu\text{m}$  mesh size) were done at 13 m to check whether the transport rate and composition were equal to that of the feeder. In equilibrium conditions, the Helley Smith gave a mean transport rate within a few percent of the feed rate and a near-equal mobility composition. Foam profiles (comparable to lacquer profiles) were made to visualise the vertical sorting.

## 2.3 Setup of experiments in a sediment recirculation flume

Three experiments were done in the Zandgoot flume at WL|Delft Hydraulics, which has a length of 50 m and a width of 1.5 m (Kleinhans 2002, Blom et al. 2003). T10 had the lowest shear stress, T5 and T9 had equal shear stresses and T7 had a higher shear stress. The sediment was recirculated with sediment pumps. Bed- and water surface profiles along the flume and bedload transport were automatically collected. The experiments were started with a mixed bed of slightly bimodal sediment, installed at a bed slope that is equal to the expected water surface slope of the experiments. The flow was maintained until the system was in equilibrium (T10 and T5). The next step on the bed of T5 was to generate a flow with a higher bed shear stress until a new equilibrium was reached (T7), and then again lower (T9) without remixing the bed. Samples have been taken from the transported sediment that was measured automatically in the recirculation system.

## 2.4 Flow and sediment parameters

From the slope and the hydraulic radius ( $R_c$ ) the total shear stress ( $\tau$ ) was determined with  $\tau = \rho g R_c i$  ( $\rho$ =density of water,  $g$ =gravitational acceleration). The hydraulic radius was corrected for side-wall roughness with the method of Vanoni-Brooks. The dimensionless shear stress is computed as  $\theta = \tau / [(\rho_s - \rho)gD]$ , in which  $\rho_s$ =density (of sediment),  $g$ =gravitational acceleration and  $D$ =sediment diameter (median m or mean 50 or 90<sup>th</sup> percentile). The dimensionless shear stress on grains is computed as  $\theta'_{50} = \tau' / [(\rho_s \rho)gD_{50}]$ , in which  $\tau'$ =shear stress on the grains, computed as  $\tau' = \rho g [u/C']^2$  in which  $u$  is the depth-averaged flow velocity,  $C'$  is the grain-related Chézy coefficient:  $C' = 18 \log[12R_c/ks']$ , with  $ks'$  the grain roughness, assumed to be equal to the  $D_{90}$  of the sediment.

## 3. Results

### 3.1 Sediment feed flume

Near the end of the Equ2 and Equ3 experiments, the composition of the transported sediment is almost equal to that of the original bed sediment and feeder sediment. This shows that all the grain sizes were in motion in almost the same abundance as they occur in the bed sediment, approximating equal mobility.

The dunes in Equ2 were much more regular than those in high discharge, in the sense that the latter had more curved crest-lines and deep scour pits every now and then, while the regular ones were more

straight-crested and did not have pronounced scour pits. The dunes in the high shear stress in Equ3 are about twice as high as in the low shear stress Eq2. From the time series taken at a single position, probability distributions of the bedlevel were computed (Fig. 2). These distributions indicate the variations of bedlevel due to passing dunes, and normalized with respect to the average bed level at that position in that time period. The Equ3 experiments has a skewed distribution with much deeper dune troughs than dune tops, while the distribution for Equ2 is about symmetrical. The distribution for Equ1 is fully determined by grain and armour dynamics.

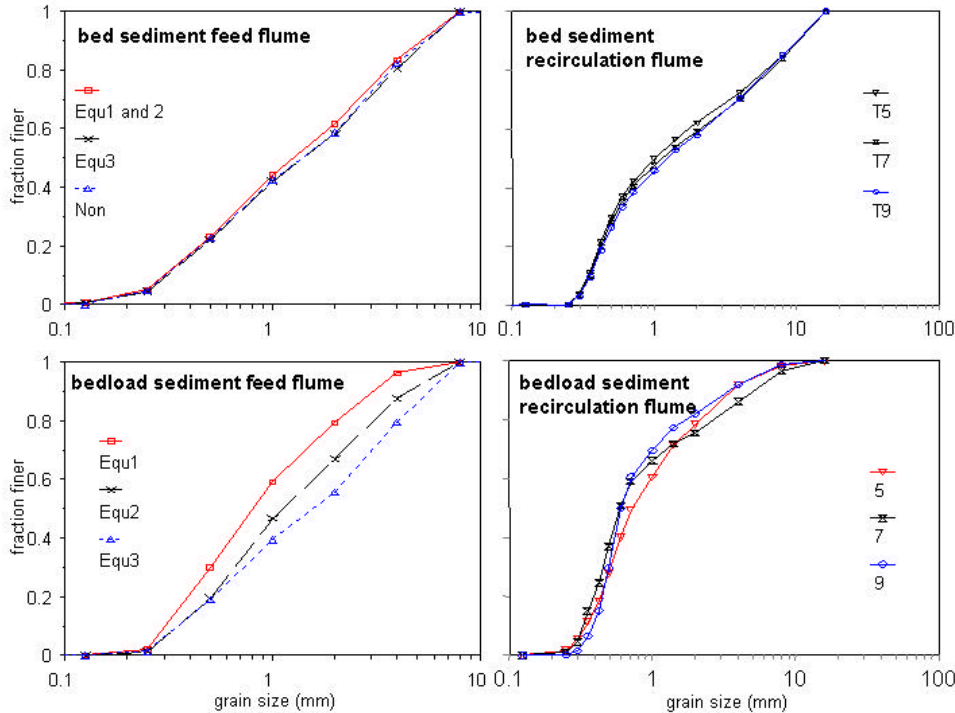


Fig. 1 – Grain size distributions of the bed sediment (equal to the feed sediment) and the bedload sediment at the end of the feed flume experiments (a) and the bed sediment and recirculated sediment of the recirculation flume experiments (b).

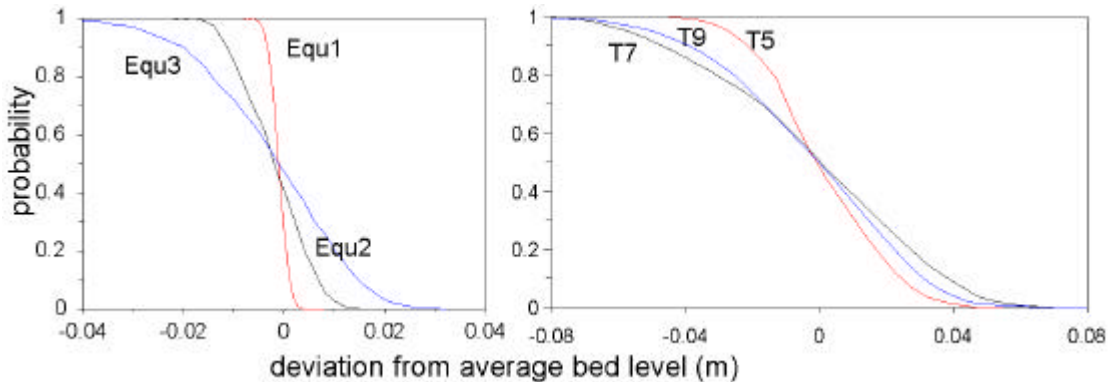


Fig. 2 – Probability distributions of the bed surface.

### 3.2 Sediment recirculation flume

Experiments T10 and T5 had barchan dunes whereas T7 and T9 had slightly irregular 2D dunes. The bedload composition in all experiments is finer than the original bed sediment (Fig. 1), but the finest in T9 because most gravel was worked downwards in T7 and was no longer entrained in the shallower dune troughs in T9. Consequently, the bedload compositions of T5 and T9 are different even though the shear stresses were approximately the same. The bed level distributions were computed from the downstream half of a number of profiles along the flume after linear detrending of the profile (Fig. 2). Comparison of T5, T7 and T9 in Fig. 2 reveals a close resemblance of T7 and T9 even though the

shear stress in T7 is larger than in T9. So, relative to T5, the scour holes in T9 are much more pronounced. The reason is that in T5 and T7 there was a gravel layer beneath the troughs which hindered the trough scour, whereas in T9 the gravel had been worked down too deep for the dunes to be affected. See also Kleinhans et al. (2002) and Blom et al. (2003).

## 4. Discussion

### 4.1 Causes of dune irregularity

Reineck & Singh (1973) describe the transition from 2D to 3D features as going from straight-crested, undulatory dunes (with continuous wavy crests), lunate (non-continuous crestlines and spoon-shaped scours) to linguoid dunes (tongue-formed like bars in shallow rivers). The dune irregularity according to Reineck and Singh is mostly based on planform. It is unclear how the trough irregularity is related to these dune types. There is a suggestion that linguoid dunes occur in small water depths whereas lunate dunes occur in large water depths, but this has not been verified and the cause of formation of these dune types remains unclear. Another interesting point is the formation of 3D megaripples (possibly equivalent to dunes) by waves and currents in estuaries and shallow seas. It has been suggested (e.g. Boothroyd & Hubbard 1975) that also in the case of asymmetric unsteady flow and waves the effective shear stress determines whether the megaripples are 2D or 3D, but this has not been corroborated with experiments and how to define the effective shear stress remains unclear (see Kleinhans et al., this volume). The case of unsteady flows over mixed sediments has barely been touched (van Santen in prep.). The results presented in this paper refer only to 2D 'straight-crested' dunes, moderately transitional 2D-3D 'undulatory' dunes, and 3D 'lunate' dunes.

The probability distributions of bed levels for 3D dunes (Equ3) at high shear stress have a much longer tail down into the bed than for 2D dunes (Equ2) in lower shear stress (Fig. 2). Dunes in uniform sediment become more irregular (3D) when the flow velocity, the water depth and the grain size is increased (Reineck & Singh 1973, Boothroyd & Hubbard 1975, Costello & Southard 1981, Terwindt & Brouwer 1986). From the feed flume experiments it can be concluded that the same is true for non-uniform sediments if lag layer formation is not allowed.

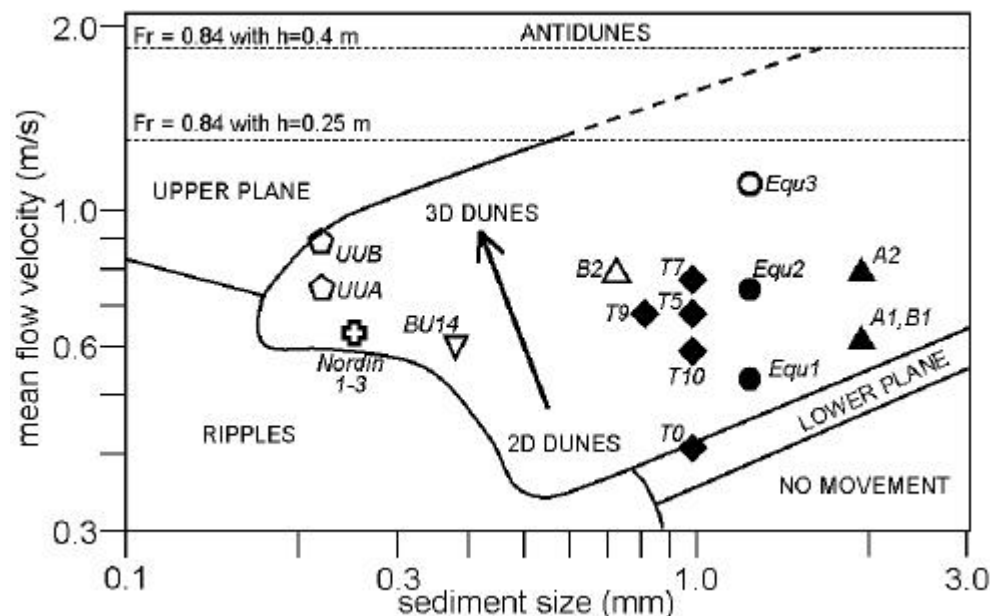


Fig. 3 – Bedform stability diagram of Southard & Boguchwal (1990) from their Figures 10.3 and 10.8 for water depths of 0.1-0.4 m. Open symbols represent 3D dunes, closed symbols 2D dunes. The transition from dunes to antidunes occurs above Froude numbers of 0.84, which is given for two water depths in the graph.

To demonstrate the consistency of three-dimensionality of the dunes, the available experiments reported in this paper and from literature are plotted in the bedform stability diagram of Southard & Boguchwal (1990, their Fig. 5) in which the dune stability field is divided into 2D and 3D regimes.

The experiments plotted are Equ1-3 (feed flume) of Kleinhans (2003), the barchan dunes of A1 and B1, 2D dunes of A2 and 3D dunes of B2 (recirculation flume) from Blom et al. (2003) (with water depths of 0.16-0.38 m) (sediment size of B2 smaller due to ‘inmixing’ of fine underlying layer), lower plane bed of T0, barchan dunes of T5 and T10 and 2D dunes of T7 and T9 (recirculation flume) from Kleinhans et al. (2002) and Blom et al. (2003) (with water depths from 0.2-0.35 m) (sediment size of T9 smaller due to deposition of gravel), 3D dunes of BU14 Leclair & Blom in press (recirculation flume), 3D dunes of unpublished uniform sand runs UUA and UUB by Utrecht University in recirculating Sandflume WL|Delft Hydraulics, and runs 1-3 (river) of Nordin (1971) with uniform sediment. The diagram clearly has some predictive power for three-dimensionality.

Leclair & Blom (2001) compared the probability distributions of the bed surface for the experiments A1 and A2 of Blom et al. (2003) and 29SAFL of Leclair & Bridge (2001), both in a recirculation flume, of which the former were done with a wide sand-gravel mixture while the latter was done with a narrow sand mixture. The wide mixture had a more or less symmetric probability distribution, while the narrow mixture had a long tail from the deep irregular scour. From the photographs in Blom et al. (2003) and Leclair & Blom (2001) it is obvious that the dunes in the narrow mixture (29SAFL) were in the three-dimensional regime, while those in the wide mixture (A1, A2) were in the two-dimensional regime as discussed before. Leclair & Blom attributed the difference to the presence of coarse sediment in the trough zone which is less mobile due to the low shear stress. In the light of the analysis above, it must be questioned whether lag layer formation inhibited irregular trough scour or the shear stress was too low for 3D dunes in the A1 and A2 experiments, or a combination of both.

#### 4.2 Mixture feedbacks on dune irregularity

For the understanding of the feedback of mixture effects on dune irregularity it is convenient to discuss three comparisons:

1. between the feed and recirculation flume;
2. between the fully mobile gravelly layer and totally immobile gravel lag;
3. between equal mobility and selective transport (here for the sake of discussion considered to occur in unimodal and bimodal sediments respectively).

1. The results in the feed flume indicated that dune irregularity depends on shear stress (flow velocity in Fig. 3 combined with the water depth for which it is valid) in the same way as for uniform sediment when the formation of coarse layers is inhibited. The recirculation flume experiments in contrast demonstrated the two ways in which such a coarse layer affects dune irregularity.

In extreme cases (very wide mixtures, low shear stresses and fine sediment supply), isolated barchan dunes migrate over a stable armour layer (Kleinhans et al. 2002), and the trough-scouring flow is ineffective. Thus, the exchange of sediment between the bedload and substrate sediment through the armour layer is insignificant. The dunes are ‘irregular’ in planform (barchanoid) but do not have irregular scour depths. In this case the mixture feedback on trough scour-related irregularity is strong and outweighs the shear stress control on irregularity. Moreover, it is completely controlled by either the bimodality of the sediment and/or the upstream sediment supply (recirculation) which is much finer than the bed sediment, both resulting in the low mobility of coarse sediment.

2. In a feed flume an armour layer is dynamic whereas in a recirculation flume or with a fine upstream sediment supply or without sediment supply at all, the armour layer becomes stable. The fully mobile armour layer is able to adapt to changing conditions, whereas the stable armour layer usually needs a shear stress above a high critical value before it is broken up. Equivalently for the duned bed, the coarse layer formed at the base of dunes can be characterised as mobile or stable. So, in stable coarse layer-forming conditions (sediment supply is limited) the stability of the coarse layer will outweigh the tendency of dunes to scour their troughs, and the dunes remain isolated barchanoids. In mobile coarse layer-forming conditions dunes will be able to scour their troughs according to the tendency to become more irregular. In other words, there barely is a feedback in the latter conditions. The mobility of the coarse layer is related to point 3.

3. In the extreme case of equal mobility (Parker & Klingeman 1982), lag layers will not form because the gravel is not less mobile than the rest of the sediment. However, experimental mixtures and river sediments commonly deviate from equal mobility (Wilcock 1993), therefore gravel lag layers may form. The exact shape of the grain size distribution (skewness, bimodality, ratio of gravel and sand, etc.) has a secondary but important effect on the mobility (Kuhnle 1993, Shvidchenko et al. 2001), but

for the present discussion a mixture is simply characterised as unimodal or bimodal. Bimodal mixtures show the largest difference in mobility between coarse and fine sediment (Wilcock 1993). Experiments with extremely bimodal sediment are reported by Hooke (1968), where a pea gravel lag in dunes in fine sand hinder the deep scour erosion, and by Van der Zwaard (1973) with comparable results in a bimodal mixture of coarse sand and coarse gravel. Thus, gravel lag formation is more likely to occur in bimodal sediment than in unimodal sediment.

Consequently, a unimodal mixture in a feed flume (in equilibrium) will probably result in equal mobility and no lag layer, but a bimodal mixture not necessarily so. In a recirculating flume both unimodal and bimodal mixtures will probably result in selective transport conditions over a coarse, less mobile or immobile layer. Concluding, the mixture feedback on dune irregularity is weak in conditions where the sediment supplied upstream resembles the substrate sediment, whereas it is strong in conditions where the sediment supplied upstream is finer than the substrate. In other words, the mobility of the coarse sediment in the trough zone is not only a function of the shear stress and the trough depth, but also of the composition of feed or recirculated sediment relative to the sediment in the (active) bed (or, alternatively, the hiding function which is in itself a function of vertical sorting and experimental setup). This control must be taken into account when experimental bed level probability distributions from sediment feed and recirculation setups are compared and interpreted with the aim to apply the resulting model to natural streams.

## 5. Conclusions

The dune irregularity (expressed as a probability distribution of bed levels) in the absence of coarse sediment layer formation is related to dimensionless shear stress in the same way as uniform sediment. A negative feedback by vertical sorting (coarse layer formation) is likely to occur in mixtures with non-equal mobility such as bimodal sediments, and in conditions where the sediment supplied upstream is finer than the substrate. The two common experimental setups of sediment feed and recirculation represent two different, extreme cases of upstream sediment supply compared to natural streams, which must be taken into account in the use of experimental data of both vertical sorting and dune irregularity for future models.

The latter issue could be investigated further with existing data and feed flume experiments with varying feed sediment composition. Additionally, the shape of the bed level probability function needs to be parameterised; in specific the shape of the tail into the bed. The effect of water depth on the position of data points in the bedform stability diagram might be removed by using dimensionless grain shear stress rather than flow velocity, which would allow comparison with field data and removal of scale effects on dunes in flume experiments.

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