Fine sediment in mixed sand-silt environments impact bedform geometry by altering sediment mobility

S.I. de Lange[1], I. Niesten[1], S.H.J. van de Veen[1], J.H. Baas[2], J. Lammers[1], K. Waldschläger[1], D. Boelee[1], A.J.F. Hoitink[1]

[1]Wageningen University, Department of Environmental Sciences, Hydrology and Environmental Hydraulics, Wageningen, the Netherlands
[2]School of Ocean Sciences, Bangor University, Menai Bridge, United Kingdom

Key Points:

- Adding finer, non-cohesive material to a sand bed increases the mobility of the sand, resulting in an increased dune length.
- Adding finer, weakly-cohesive silt to a sand bed, decreases the mobility of the sand, which hampers dune formation and growth.
- Sediment bed composition does not directly impact total hydraulic roughness, but indirectly affects it via altering the bed morphology.

Corresponding author: Sjoukje de Lange, `sjoukje.delange@wur.nl`

Abstract

Geometric characteristics of subaqueous bedforms, such as height, length and leeside angle, are crucial for determining hydraulic form roughness and interpreting sedimentary records. Traditionally, bedform existence and geometry predictors are primarily based on uniform, cohesionless sediments. However, mixtures of sand, silt and clay are common in deltaic, estuarine, and lowland river environments, where bedforms are ubiquitous. Therefore, we investigate the impact of fine sand and silt in sand-silt mixtures on bedform geometry, based on laboratory experiments conducted in a recirculating flume. We systematically varied the content of sand and silt for different discharges, and utilized a UB-Lab 2C (a type of acoustic Doppler velocimeter) to measure flow velocity profiles. The final bed geometry was captured using a line laser scanner. Our findings reveal that the response of bedforms to an altered fine sediment percentage is ambiguous, and depends on, among others, bimodality-driven bed mobility and sediment cohesiveness. When fine, non-cohesive material (fine sand or coarse silt) is mixed with the base material (medium sand), the hiding-exposure effect comes into play, resulting in enhanced mobility of the coarser material and leading to an increase in dune height and length. However, the addition of weakly-cohesive fine silt reduces the mobility, suppressing dune height and length. Finally, in the transition from dunes to upper stage plane bed, the bed becomes unstable and bedform heights vary over time. The composition of the bed material does not significantly impact the hydraulic roughness, but mainly affects roughness via the bed morphology, especially the leeside angle.

Plain Language Summary

Underwater bedforms, such as dunes, are often found on the bed of rivers and deltas. These rhythmic undulations have specific shapes and sizes, and they affect how water flows. When the bed of the river is made up of sand, we can predict the dune height and length. However, mixtures of different-sized sediments are common in rivers, and it is unknown how this impacts the geometry of the dunes. Therefore, we did experiments in a flume, a laboratory facility to simulate a river, and we tested different sediment bed mixtures. We found that adding non-cohesive fine particles to the base material caused the base material to be more mobile, leading to longer dunes. However, when adding weakly-cohesive fine particles, the effect was the opposite, and the dunes became shorter due to the limited mobility of the sediment. Finally, we observed that under high flow conditions, the bed became unstable and different dune shapes occurred. We found that the friction the water experiences is not directly impacted by the sediment bed mixtures, but is mostly affected by the shape of the bedforms.

1 Introduction

River bedforms are ubiquitous in low-land rivers, and they are known to impact the river by altering its hydraulics, ecology, and sediment balance. The geometry of river bedforms, especially dunes, impacts the fairway depth (ASCE Task Force, 2002; Best, 2005), adds to the form roughness of the river bed (Warmink et al., 2013; Venditti and Bradley, 2022), and determines suitable foraging places for fish (Greene et al., 2020). It is therefore useful to predict the geometry of bedforms without having to perform regular field measurements. In non-supply limited conditions, river dunes may scale with flow depth (Allen, 1978). However, more recent studies have reinstated the observations by Yalin (1964), Van Rijn (1984), and Karim (1995), indicating a relation between bedform geometry and some measure of transport stage (Bradley and Venditti, 2019; Venditti and Bradley, 2022), where transport stage represents the ratio between flow strength and the mobility of the bed material. Dune length increases with transport stage, while dune height increases with transport stage until a maximum is reached, whereafter the height decreases and the bedforms start to wash out (Baas and Koning, 1995; Bradley and Venditti, 2019). This framework effectively predicts dune height and length, despite considerable variability, which can be up to two-orders of magnitude (Bradley and Venditti, 2017). This variability may in part be attributed to the influence of bed composition on bedform geometry.

The bed composition, i.e. the grain size distribution of the bed sediment, is one of the primary determinants for bedform existence and size. Measures of grain size appear in almost all existing phase diagrams (Southard and Boguchwal, 1990; Berg and Gelder, 1993; Perillo et al., 2014), with the median grain size D_{50} as general parameterization. However, this simplification poses challenges when dealing with natural sediment mixtures characterized by complex, multimodal sediment size distributions, which are common in deltaic, estuarine and coastal environments featuring sediment mixtures of mud (i.e. clay and silt) and sand (Healy et al., 2002).

Recent research has focused on understanding how cohesive clay affects bedform geometry. It has been observed that even a small percentage of cohesive clay in sand-clay mixtures can effectively suppress bed mobility, resulting in a reduced bedform height (Schindler et al., 2015; Parsons et al., 2016) and limited bedform growth (Wu et al., 2022). It is, however, unknown what the impact of non- and weakly cohesive fine materials (silts and fine sands) is on dune morphology, despite their abundance in downriver environments.

A few studies explored the influence of silt on erodibility of the sediment bed. For instance, Bartzke et al. (2013) examined the behavior of sand (300 μm)-silt (50 μm) beds in an annular laboratory flume. They found that an increasing silt content, even at low percentages (as little as 0.18% silt), contributed to bed stabilization through a reduction in water inflow, attributed to pore-space plugging by silt. Yao et al. (2022) also reported increased stability (i.e., increased erosion threshold) with increasing silt content in their laboratory experiments, although stabilization only occurred at a silt content of >35%, when a stable silt skeleton could be formed. Opposing Bartzke et al. (2013), a change in bed stability was not observed at lower silt contents.

Additionally, Ma et al. (2017) and Ma et al. (2020) studied a silt-rich sediment bed (D_{50} = 15 - 150 μm) with low dunes in the Yellow River. Ma et al. (2020) showed that the presence of fine sediment (silt) led to a shift from a low-efficiency sediment transport regime (following the Engelund-Hansen equations (Engelund and Hansen, 1967)) to a high-efficiency regime. The high-efficiency regime prevailed for sediment beds with a medium grain size smaller than 88 μm, and, in the transitional range (88 μm < D_{50} < 153 μm), the existence of this regime depended on sorting of the material ($\sqrt{D_{84}/D_{16}}$). They argued that the shift from a low- to a high-efficiency transport regime resulted from the transition from mixed load to suspended sediment transport, caused by the presence of silt.

Yet, none of these studies discussed the potential impact of silt content on bedforms. This is an important research gap, because an increase in bed stability, as observed by Bartzke et al. (2013) and Yao et al. (2022), could theoretically reduce bedform formation and growth due to a decrease in sediment transport, whilst Ma et al. (2020)'s suspension-load dominated high-efficiency regime would also mean suppression of bedform formation and growth, but then because bedload transport gets increasingly replaced by suspended load transport, which is incapable of forming bedforms. Clearly, the effect of silt in sand-silt mixtures on the resulting bedform geometry is largely unexplored. Therefore, our research seeks to address the following question: What is the influence of the fraction non-cohesive and weakly cohesive fine sediment in sand-silt mixtures on the dynamic equilibrium bedform geometry and the resulting hydraulic roughness?

To answer this question, we conducted 52 laboratory experiments in a recirculating flume, in which the influence of fine sand and silt percentage in sand-silt mixtures on bedform geometry was studied. For three flow velocities, three different sediment mixtures, largely falling within the studied range of Ma et al. (2020), were tested by systematically mixing various fractions of fine sand, coarse silt and fine silt with a coarser base material of

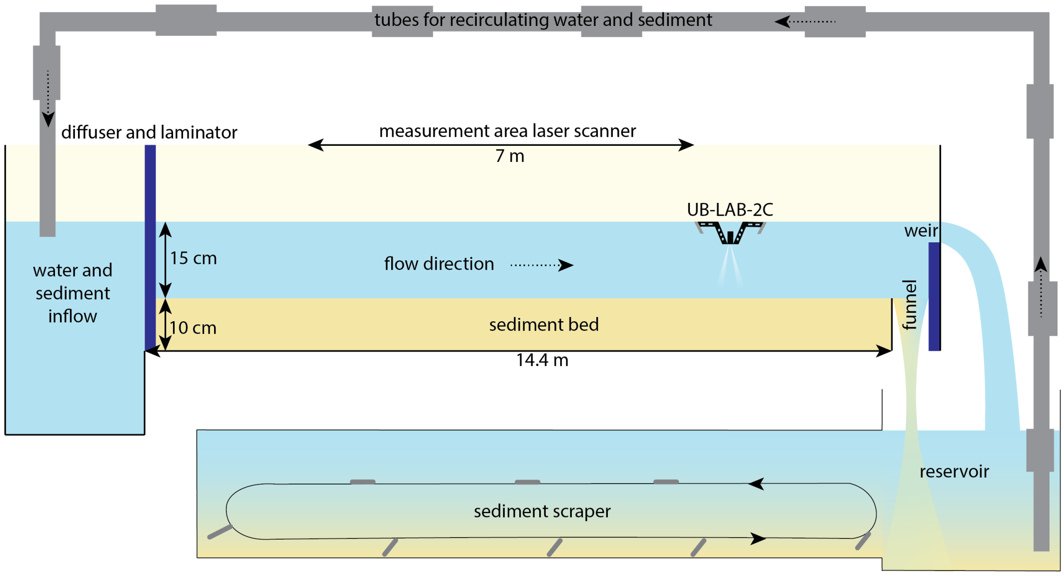

Figure 1. Schematic drawing of the experimental setup. The flume recirculates both water and sediment.

medium sand. These experiments allowed us to assess how different sizes of fine sediment in a sand-silt mixture affect the transport stage and the resulting bedform geometry under different flow conditions. In the following sections, we provide a detailed description of the experimental setup, after which we discuss the different equilibrium bedform geometries that resulted from the experiments. We argue that the hiding-exposure effect enhances the mobility of the coarser fraction, whereas cohesion from fine silt decreases the bed mobility, leading to deviations from the expected relationship between transport stage and bedform dimensions.

2 Methods

2.1 Experimental setup

The experiments were conducted in a tilting flume with recirculation facilities for both water and sediment in the Kraijenhoff van de Leur Laboratory for Water and Sediment Dynamics of Wageningen University and Research (Figure 1 and 2). The flume has an internal width of 1.20 m, a length of 14.4 m, and a height of 0.5 m. The water level is controlled by adjusting a downstream weir. A diffuser (Figure 2a) at the upstream part ensures that the inflow is distributed over the entire width of the flume. The diffuser is followed by a stacked pile of PVC tubes that serve as a laminator, suppressing turbulence at the inflow section. At the end of the flume, a funnel was installed to channel bedload material to a lower reservoir (Figure 1), and to prevent deposition in front of the weir. A continuously running sediment scraper ensures that the sediment stays in suspension in the lower reservoir, upon being pumped back to the inflow of the flume. At the end of one experiment (35% fine sand, medium discharge) the sediment funnel was clogged and the sediment was not fully recirculated. This run was excluded from the analysis.

The flow depth was set to 15 cm, measured from the initial flat sediment bed, and it was kept the same for all experimental runs by adjusting the weir height. The slope was set to 0.01 m m^{-1}. Experimental runs were performed for different discharges (low: 45 L s^{-1}; medium: 80 L s^{-1}; high: 100 L s^{-1}), to be able to distinguish the effects of different trans-

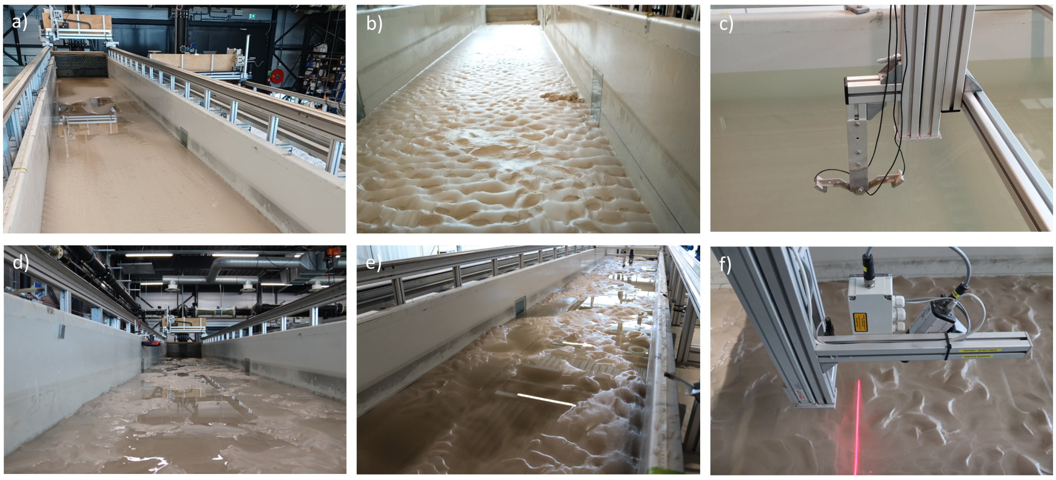

Figure 2. Pictures of the laboratory flume and the instrumentation. a) Flume with flatbed, facing upstream, including the upstream-located diffuser. b) Bed covered with small bedforms, facing downstream, including the downstream-located weir. c) UB-Lab 2C flow velocity profiler. d) Dune-covered bed, facing upstream. e) Dune-covered bed, facing downstream, with the UB-Lab 2C in background. f) Line laser scanner.

port stages on bedform morphology. The discharge was monitored and regulated with an electromagnetic flow meter. The corresponding calculated width- and depth-averaged flow velocities were 0.25, 0.44 and 0.56 m s^{-1}, the corresponding depth-averaged flow velocities in the middle of the flume (measured with an UB-Lab 2C, see section 2.2) were slightly larger due to a side-wall effect (0.30, 0.45 and 0.58 m s^{-1}, respectively). The experiments were run for 12, 5 and 3 hours for the low, medium, and high discharges, respectively. Based on the ripple size predictor of Soulsby et al. (2012), the medium-sand ripples formed in the low-discharge experiments reached about 80% of their equilibrium height and length after 12 hours. Their planform at this development stage was linguoid, which agrees with the planform predicted by ripple development model of Baas (1999). Naqshband et al. (2016) studied the dune equilibrium time for medium sand (290 μm). Their equilibrium dimensions were reached after 3 hours for the experiments with a flow velocity of 0.64 m s^{-1} and after 1.5 hours for 0.80 m s^{-1}. This suggests that the dunes formed at medium and high discharges in the present experiments reached equilibrium size.

The flow was sub-critical and turbulent during all experiments, determined by the Froude number, Fr (-), being smaller than 1 (0.30, 0.54 and 0.69, respectively) and the Reynolds number, Re (-), being larger than 4000 (38000, 67000, 83000, respectively), calculated with:

$$Fr = \frac{u}{\sqrt{gh}} \tag{1}$$

$$Re = \frac{hu}{\nu} \tag{2}$$

where u is the time and depth-averaged flow velocity (m s^{-1}), g is the gravitational acceleration (9.81 m s^{-2}), h is the water depth (0.15 m), and ν is the kinematic viscosity (m^2 s^{-1}), which is weakly dependent on water temperature, t (°C), as $\nu = 4 * 10^{-5}/(20 + t)$. Here, ν = 1.05 * 10^{-6} m^2 s^{-1} for 18 °C is used.

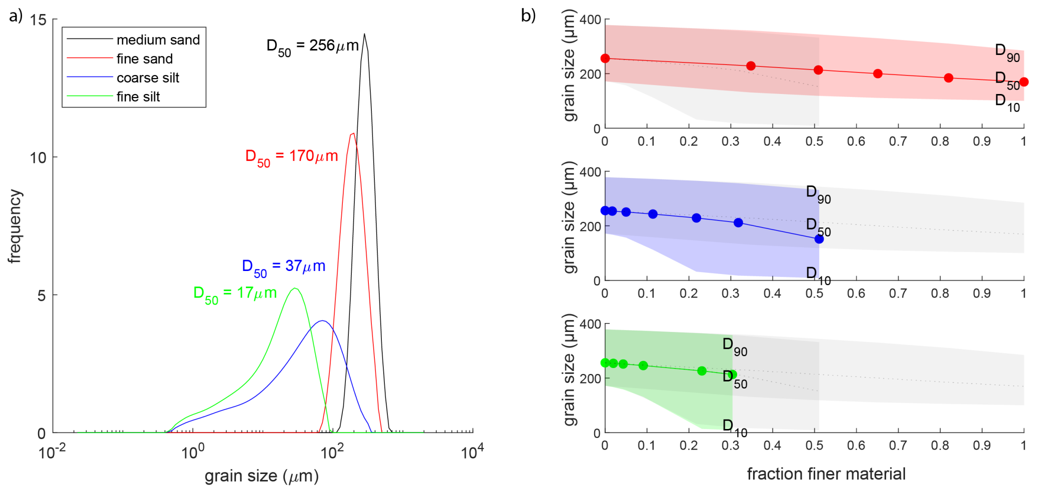

Figure 3. a) Grain-size distributions of the sediments used in the experiments. b) D_{10}, D_{50} and D_{90} of the tested mixtures, in which the finer material (fine sand, coarse silt or fine silt) is mixed with the base material (medium sand).

A sediment bed with a thickness of 0.10 m was applied, which consisted of a mixture of two grain sizes: a base sediment of medium sand (median size, $D_{50} = 256$ μm), mixed with fine sand ($D_{50} = 170$ μm), coarse silt ($D_{50} = 37$ μm) or fine silt ($D_{50} = 17$ μm) (Figure 3a and Supplementary Figure S1 for images of the sediment). All sediments were composed of silica (SiO_2). The particle size distribution of the original sediments was measured with a Mastersizer 3000 (Figure 3). The fine sand and coarse silt are non-cohesive, whereas the fine silt could be classified as weakly-cohesive (Wolanski, 2007), confirmed by visual observation of the sticky fine silt slurry and a significantly higher submerged angle of repose (40° instead of 30° for sand). No visible flocculation of the silt fraction occurred during the experiments.

The weight percentage of finer material mixed with the base material ranged from 0 to 100 wt% for fine sand, to 51 wt% for coarse silt (with 49 wt% medium sand) and to 30 wt% for fine silt (with 70 wt% medium sand). In total, 17 different mixtures were tested, which were all exposed to the low, medium and high discharge. In Table 1, an overview of the experimental mixtures is given. The D_{50} and 90th-percentile, D_{90}, values of the mixtures hardly changed when adding finer material, but the 10th-percentile, D_{10}, values dropped significantly when adding coarse or fine silt (Figure 3b).

2.2 Instrumentation

A line laser and 3D camera (Figure 2f), equipped with Gigabit Ethernet (SICK, 2012), was used to scan the bed topography. The devices were mounted on a measurement carriage that moved on fixed rails along the flume. After every experimental run, the flume was slowly drained, and an area of 7 x 1 m was recorded in three parallel, partially overlapping, swaths, with a resolution of 0.1 mm. See Ruijsscher et al. (2018) for a detailed description of the line laser scanner.

During the first and last 30 minutes of an experimental run, an UB-Lab 2C (UBERTONE) (Figure 2c) was deployed to measure flow velocity profiles. The UB-Lab 2C is an ADVP (acoustic Doppler velocity profiler, e.g. Hurther and Lemmin (2001) and Mignot et al. (2009)), which measures a two-component velocity profile at high spatial (1.5 mm) and temporal resolution, here 10 to 15 Hz. An acoustic signal is transmitted along a single beam and received by two receivers under different observation angles. The resulting 2-component

Table 1. Overview of the performed experiments. Seventeen different sediment mixtures were tested, in which the type and percentage of fine material relative to the coarse material (base material) varied per experimental run. Each experiment with a distinct mixture was conducted for low, medium and high discharge, resulting in 51 experiments. * the experiment with medium discharge was excluded from analysis because of clogging of the pumps.

experiment number	% fine / % coarse
base experiment	
1	0/100
experiments with fine sand	
2-4	35/65*
5-7	51/49
8-10	65/35
11-13	82/18
15-18	100/0
experiments with coarse silt	
19-21	2/98
22-24	5/95
25-27	11/89
28-30	22/78
31-33	32/68
34-36	51/49
experiments with fine silt	
37-39	2/98
40-42	4/96
43-45	9/91
46-48	23/77
49-51	30/70

vector is than projected to yield the 2-dimensional velocity in the streamwise direction (u) and vertical direction (w) along the beam (1D-profile). The emission frequency was set to 1 MHz with a bin size of 1.5 mm. The pulse repetition frequency ranged from 1200 to 1800 Hz for low and high discharge, respectively.

2.3 Data analysis

2.3.1 Sediment characterization

The behavior of the sediment in the experiments was estimated from the span value of the sediment-size distribution and the dominant way of sediment transport. This information was later used to interpret the observed bedform patterns.

The span value of the tested mixtures was used as a measure of distribution width, and was defined as:

$$SV = \frac{D_{90} - D_{10}}{D_{50}} \tag{3}$$

The sorting was determined as:

$$\sigma_g = \sqrt{\frac{D_{84}}{D_{16}}} \tag{4}$$

To determine the dominant way of transport, the ratio between the settling velocity of a particle, w_s, and the shear velocity, u^*, was calculated. If this ratio is larger than 3, the dominant transport mode is expected to be bedload, and if the ratio is smaller than 0.3, the dominant mode is expected to be suspended load (Dade and Friend, 1998). In between these values, the transport mode is mixed.

The settling velocity of a particle was approximated with (Ferguson and Church, 2004; Dietrich, 1982):

$$w_s = \frac{\rho_r g D_{50}^2}{C_1 \nu + \sqrt{0.75 C_2 R g D_{50}^3}} \tag{5}$$

where ρ_r is the relative submerged density $= (\rho_s - \rho_w)/\rho_w$, and $C_1 = 18$ and $C_2 = 1$ for natural grains (Ferguson and Church, 2004). The D_{50} of the original sediments was used rather than the D_{50} of the mixture, giving a transport mode for the base sediment and the finer fraction separately. This approximation was verified by visual observation through a window in the side of the flume.

2.3.2 Bedform geometry

Final bed configurations were determined from the bed elevation data obtained with the line laser scanner. Five longitudinal transects were constructed across the width of the flume, with an interspacing of 200 mm. The resulting transects served as input for the bedform tracking tool of Mark and Blom (2007), which gives bedform geometry based on specific detrending lengths, used to differentiate between bedform scales. Two bedform length scales were identified: 150 ± 100 mm (hereafter referred to as small bedforms), and 1100 ± 400 mm (referred to as large bedforms). Small bedforms were observed in the low-discharge experiments, whilst larger bedforms were observed in the medium and high-discharge experiments, and the bedform tracking tool was applied accordingly. Only if the bedform occurred in at least two profiles of a bed scan, bedform statistics were calculated.

Bedform characteristics (Figure 4) in this study included bedform height, Δ (m), the vertical distance between crest and downstream trough; bedform length, λ (m), the horizon-

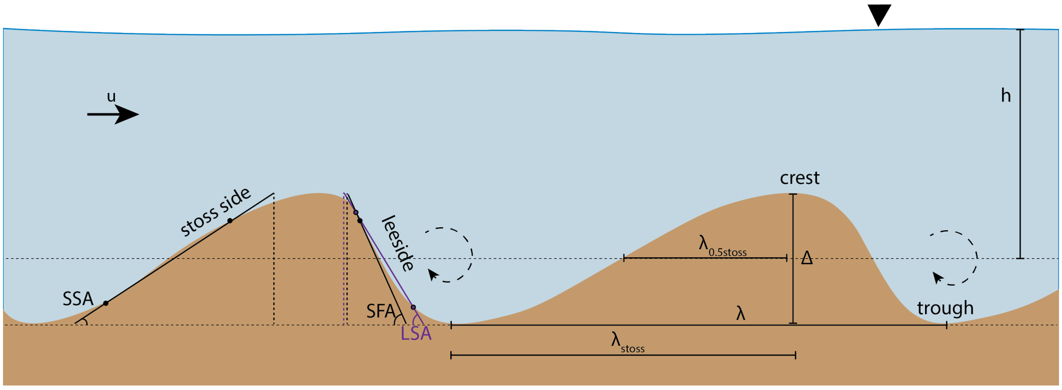

Figure 4. Definition of the bedform characteristics, showing the bedform height (Δ), the length (λ), the total length of the stoss side (λ_{stoss}) and the length of the stoss side at 0.5*Δ ($\lambda_{0.5stoss}$), the leeside angle (LSA), in which the upper and lower 1/6th of the leeside is excluded, the stoss-side angle (SSA), also excluding the upper and lower 1/6th of the stoss side, and the slip-face angle (SFA), which is the steepest part (95-percentile) of the leeside. The steepest part of the leeside is indicated with a small purple marker, and the location of the upper and lower 1/6th of the lee and stoss side are indicated with a small black marker.

tal distance between two subsequent crests; leeside angle, LSA (°), the slope angle derived from a linear fit of the bedform's leeside, excluding the upper and lower 1/6 of the bedform height; stoss-side angle, SSA (°), calculated similarly to the leeside angle; and the slip-face angle, SFA (°), the steepest part of the leeside, calculated as the 95-percentile of the distribution of angles along the leeside. The bedform roundness index, BRI, of the small bedforms was defined as the ratio between the length from the dune crest to the stoss side at 0.5 times the dune height ($\lambda_{0.5stoss}$) and the length of the stoss side (λ_{stoss}) (Perillo et al., 2014; Prokocki et al., 2022). A bedform was classified as rounded if $BRI \geq 0.6$. Finally, the bedform width, W (m), was derived by constructing six cross-sectional profiles transverse to the flow, with an interspacing of 1000 mm. Next, the same bedform tracking tool was applied using the same settings as for the longitudinal profiles. The bedform width was calculated only for the low-discharge experiments, where the width of the bedforms was considerably smaller than the width of the flume.

2.3.3 Bedform geometry predictors

Various bedform geometry predictors were tested based on our data. The selected predictors for dune height and length included a measure of flow strength (Van Rijn, 1984; Venditti and Bradley, 2022), and the predictor of Soulsby et al. (2012) was used for the height and length of ripples.

Van Rijn (1984) developed an empirical dune height and length predictor, the former being dependent on the transport stage, T_{vRijn}, as measure of flow strength.

$$\Delta_{vRijn} = 0.11h\left(\frac{D_{50}}{h}\right)^{0.3}(1 - e^{-0.5T_{vRijn}})(25 - T_{vRijn}) \tag{6}$$

$$\lambda_{vRijn} = 7.3h \tag{7}$$

T_{vRijn} depends on shear stress and critical shear stress. See Appendix A for a full explanation.

Venditti and Bradley (2022) developed an empirical equation based on a different transport stage, T_{VB}, defined as $\frac{\theta}{\theta_c}$, which is the ratio of the dimensionless shear stress, θ, and critical shear stress, θ_c. The equations suitable for laboratory flows with a water depth less than 0.25 m are:

$$\Delta_{VB} = h\left(-0.00100(\frac{\theta}{\theta_c} - 17.7)^2 + 0.417\right) \tag{8}$$

$$\lambda_{VB} = h\left(0.0192(\frac{\theta}{\theta_c} - 8.46)^2 + 6.23\right) \tag{9}$$

The geometry of ripples is only dependent on a measure of grain size (D^*) and independent of transport stage (Baas, 1994; Baas, 1999). According to the equations of Soulsby et al. (2012), their geometry can be predicted with:

$$\Delta_{Souslby} = D_{50} 202 D^{*-0.554} \tag{10}$$

$$\lambda_{Soulsby} = D_{50}(500 + 1881 D^{*-1.5}) \tag{11}$$

All definitions and symbols are given in Appendix A.

2.3.4 Roughness characterization

Hydraulic roughness was estimated following two methods. Firstly, the measured velocity profiles were used, following the method of Hoitink et al. (2009). Secondly, an indirect hydraulic roughness predictor of Van Rijn (1984) was used, based on bed geometry and sediment characteristics.

The first method is based on the Law of the Wall:

$$\frac{\overline{u}(z)}{u^*} = \frac{1}{\kappa} ln(\frac{z+h}{z_0}) \tag{12}$$

where $\overline{u}$ is the mean velocity (m s^{-1}), $\kappa = 0.4$ is the Von Karman constant, h is the mean water depth (m), z is the height above the bed (m), and z_0 is roughness length (m).

For a water column that satisfies equation (12), i.e. where the velocity profiles are logarithmic (Supplementary Figure S3), the shear velocity can be determined from the slope of the velocity versus dimensionless depth σ_d (equation (B2)). This, in turn, can be used to derive roughness length and, ultimately, Manning's n, n_{man} (s m$^{-1/3}$). See Appendix B for an elaborate definition. Experiments 13-18 were excluded from analysis, since erroneous mounting caused invalid profiles.

Roughness was also approximated indirectly based on the predictor of Van Rijn (1984). The total predicted hydraulic roughness, expressed as friction factor, $\hat{f}$, results from form friction and grain friction (Einstein, 1950). The total hydraulic roughness was predicted as in Van Rijn (1984):

$$\hat{f} = \frac{8g}{(18\log(\frac{12h}{k_s}))^2} \tag{13}$$

where k_s is a measure of roughness both consisting of form roughness and grain roughness. See Appendix B for the corresponding equations.

Friction factor $\hat{f}$ can be converted to n_{man} via (Manning, 1891; Silberman et al., 1963):

$$n_{man} = \frac{R_h^{1/6}}{\sqrt{\frac{8g}{\hat{f}}}} \tag{14}$$

where R_h is the hydraulic radius, which is equal to the cross-sectional area (A) divided by the wetted perimeter (P = width + $2h$).

3 Results

3.1 Observed bed geometries

The bed geometries in the experiments were dependent on discharge (Figure 5a-c, see Supplementary Figures S2-S4 for the bed geometry of all runs), and on the addition of fine material. Below, we show the results separately for low, medium and high discharge.

3.1.1 Low discharge bed geometries

At low discharge, only small bedforms appeared on the bed (Figure 5a). The small bedforms had an average height of 0.011 m, an average length of 0.12 m and a non-rounded shape with a slip-face angle of 22°.

Bedform height and width both decreased with the addition of coarse silt and fine silt, which is especially pronounced at a silt percentage above 20% (Figure 6a). The bedform height decreased by 38% for coarse silt and 28% for fine silt compared to the experiment with pure medium sand. The corresponding decrease in length was considerably smaller (14% and 4%, respectively). This decrease in bedform height was not visible in the experiments with fine sand. Similarly, bedform width decreased by 11% and 23% for coarse and fine silt (Figure 6c), indicating that the bedforms became more three-dimensional in shape. The *LSA*, *SFA* and *BRI* of these bedforms were independent of the type and percentage of finer material added (Figure 6d-f) .

3.1.2 Medium discharge bed geometries

The bedforms generated during medium discharge were generally larger than those that emerged during low discharge, with an average height of 0.027 m, a length of 0.54 m, and a slightly lower slip-face angle of 20°. Those bedforms followed two general trends. Firstly, the runs with an increasing amount of fine sand and coarse silt showed an increase in bedform height and length (Figure 5b). Especially for the coarse-silt runs, the increase in bedform length was considerable (Figure 7b). The bedform length in these runs was on average 0.59 m for the experiments with 20% coarse silt or less, and increased to 1.1 m for the experiments with a higher coarse-silt percentage in the bed. This increase in bedform length was accompanied by a smaller increase in bedform height from 0.032 m to 0.043 m (Figure 7a). Bedform heights and lengths for the experiments with fine sand were smaller than for the experiments with coarse silt (on average $\Delta = 0.026$ m and $\lambda = 0.54$ m for fine sand, and $\Delta = 0.035$ m and $\lambda = 0.73$ m for coarse silt). The lee-face angles varied per experiment, but the slip-face angles remained relatively constant, lacking a consistent trend with increasing content of fine material (Figure 7c and d).

The experiments with fine silt revealed smaller bedforms that were larger than the bedforms in the low-discharge experiments, but comparable in planform (Figure 5d), despite the clear increase in depth-averaged flow velocity. The mean bedform length was 0.38 m, which is significantly smaller than for the experiments with fine sand and coarse silt. However, at 0.025 m, the mean bedform height is comparable to the runs with fine sand. A decrease in length and height was observed for the runs with 0 to 30% fine silt (23% decrease

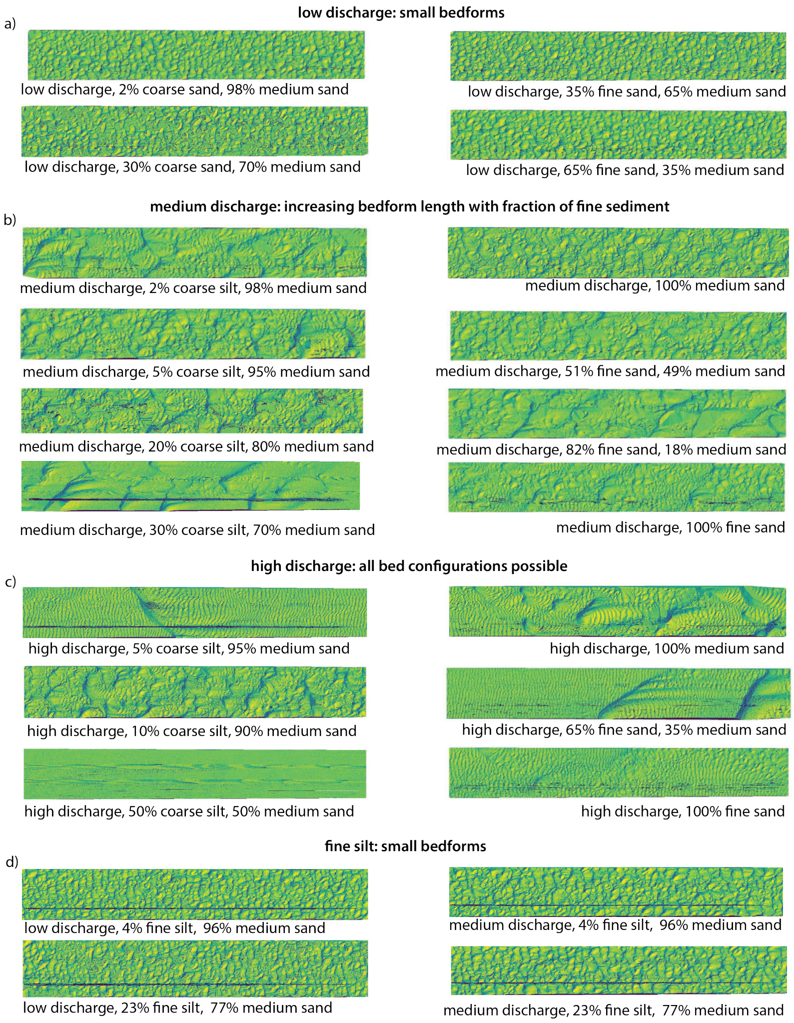

Figure 5. Dynamic equilibrium bed morphologies at the end of selected experiments. All images represent a 1 m wide and 7 m long section of flume. a) Bed morphologies at low discharge. b) Bed morphologies at medium discharge, showing increasing dune length with increasing finer material. c) Bed morphologies with large variability at high discharge. d) Impact of fine silt on bed morphology. Scans in (c) show small two-dimensional ripples superimposed on larger bedforms and flat beds. These ripples are artifacts caused by draining the flume over an almost flat bed (see Supplementary Figure S5 for verification).

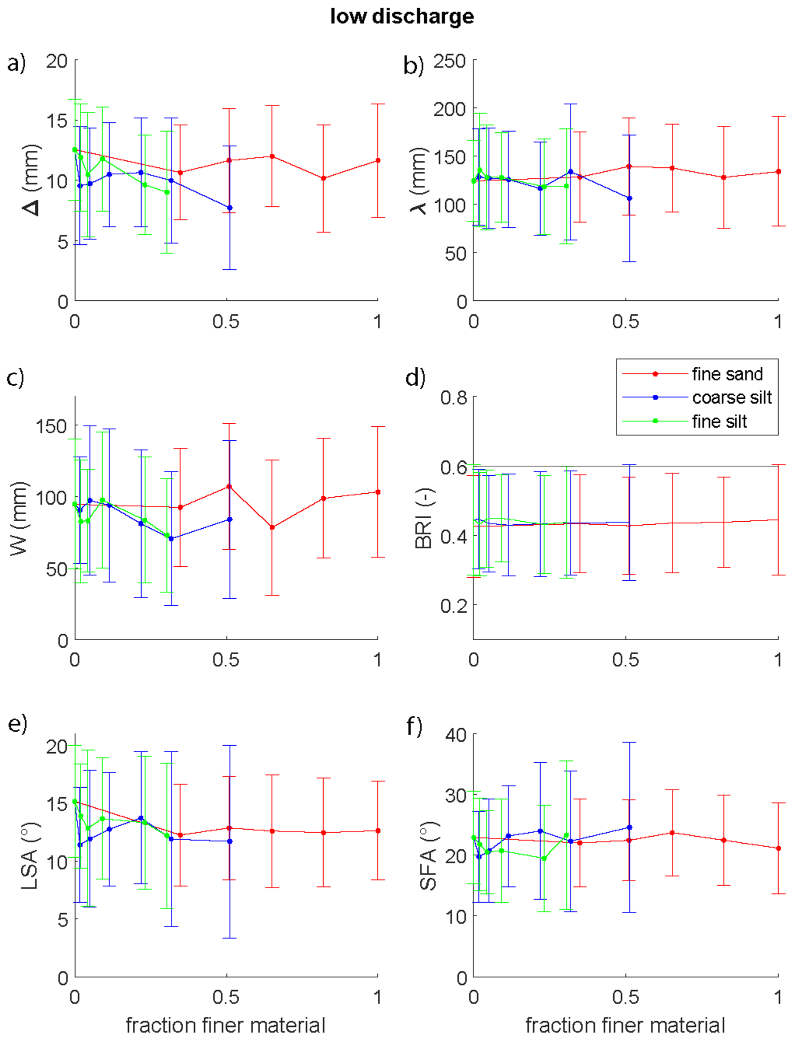

Figure 6. Bedform geometries at low discharge (45 L s^{-1}). a) Bedform height. Δ. b) Bedform length, λ. c) Bedform width, W. d) Bedform roundness index, BRI, where $BRI < 0.6$ indicates non-rounded bedforms. e) Leeside angle, LSA. f) Slip-face angle, SFA.

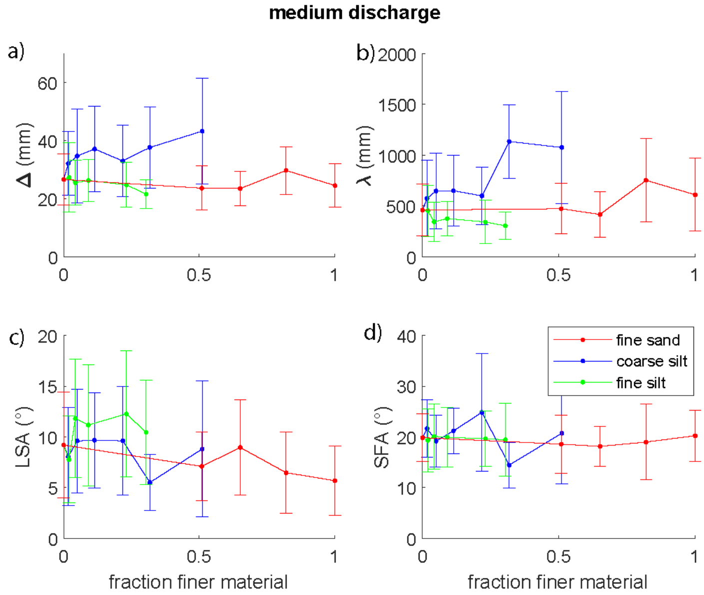

Figure 7. Bedform geometries at medium discharge (80 L s^{-1}). a) Bedform height, Δ. b) Bedform length, λ. c) Leeside angle, *LSA*. d) Slip-face angle, *SFA*.

in bedform height, 51% decrease in bedform length). Leeside angles were 28% larger than in the experiments with fine sand and coarse silt, but the slip-face angles were comparable.

3.1.3 High discharge bed geometries

The bedforms formed at high discharge were on average slightly larger than during medium discharge (Figure 8), with an average height of 0.029 m and length of 0.72 m. The slip-face angle was 18°, which was slightly lower than at medium discharge. However, the geometrical parameters were highly variable, with a standard deviation of 1.6 cm, 39 cm, 4.6° for bedform height, length and slip-face angle, respectively, and without a clear relationship with the amount of fine material. The experiments with fine silt resulted on average shorter bedform lengths and higher leeside angles than the experiments with coarse silt and fine sand, which agrees with the observations at medium discharge.

The high discharge experiments were conducted close to the suspension threshold (w_s / $u^* < 0.3$), and the bedforms started to wash out towards upper stage plane bed, when three alternating bed states were observed (Figure 5c): an almost flat bed with one or two large, steep bedforms; a bed covered with dunes; and a flat bed.

3.2 Bedform variability

Relationships between bedform geometry and transport stage, θ/θ_c, are evident from the experimental data. Bedform length increased, and leeside and slip-face angle decreased with increasing transport stage, whereas the relationship between bedform height and transport stage approached a parabola (Figure 9a-d). Additionally, the variability in bedform geometry increased with increasing transport stage, indicated by the gray shaded band in Figure 9a-d.

The near-bed velocity $U_{0.2}$, which is the time-averaged velocity at the dimensionless height above the bed of σ_d = 0.2 and directly measured with the UB-Lab 2C, is a repre-

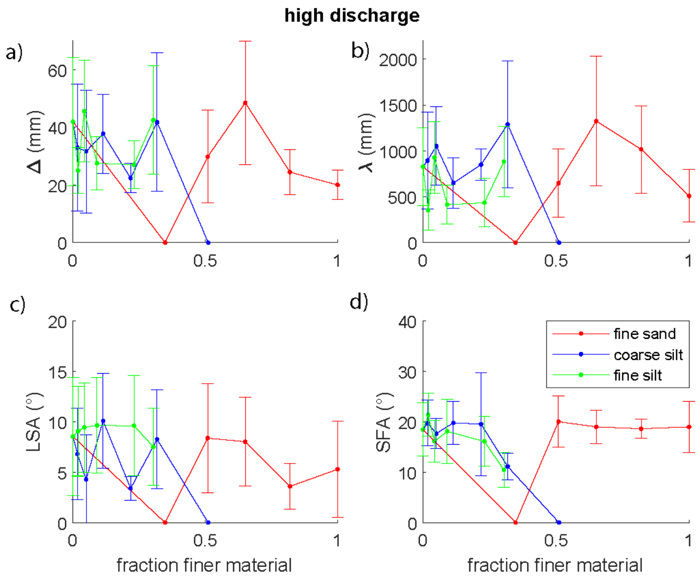

Figure 8. Bedform geometries at high discharge (100 L s^{-1}). a) Bedform height, Δ. b) Bedform length, λ. c) Leeside angle, LSA. d) Slip-face angle, SFA. Zero values indicate a flat bed.

sentation of the near-bed conditions influencing and being influenced by the bed geometry. The near-bed velocity shows a strong relation with the dimensionless bedform length (R^2 = 0.66) (Figure 9e).

The bedform height and length predictions for dunes based on Van Rijn (1984) and Venditti and Bradley (2022) are shown in Figure 9a-b. For the low-discharge runs, these predictions overestimate the measured bedform dimensions significantly. However, the ripple predictor of Soulsby et al. (2012) performs relatively well, with root-mean-square errors of 0.001 m for height and 0.02 m for length. The bedforms can therefore be classified as ripples. For the medium and high discharge runs, the Soulsby et al. (2012) equation for ripples underpredicts the bedform size significantly. These bedforms are therefore classified as dunes. The predictor of Van Rijn (1984) performs reasonably well for medium transport stages, but it mostly underpredicts bedform heights for high transport stages. The predictor of Venditti and Bradley (2022) slightly overpredicts bedform height, but the measured values are still within their margins of error. The bedform length predictor of Van Rijn (1984), which is purely based on water depth, does not capture the trend of increasing dune length with increasing transport stage. The predictor of Venditti and Bradley (2022) largely overestimates bedform length for medium transport stages, but performs better for the high transport stages by capturing the observed increase in length.

3.3 Hydraulic roughness

Hydraulic roughness, expressed as the depth-independent Manning's n and calculated via the Law of the Wall based on the velocity profiles (equation (12)), averaged 0.038. Manning's n increased with increasing leeside angle (R^2 = 0.31) and decreasing bedform length (R^2 = 0.40) (Figure 10c-d). The relation with leeside angle stands out (Figure 10c), since the ripples and dunes are both part of the linear correlation, whereas no relation between ripple length and roughness was observed. Generally, the roughness was larger during the experiments with fine silt (Figure 10) and the experiments with a rippled bed (on average 0.039). The larger roughness is likely to be related to the relatively high leeside angle of the bedforms observed in those experiments.

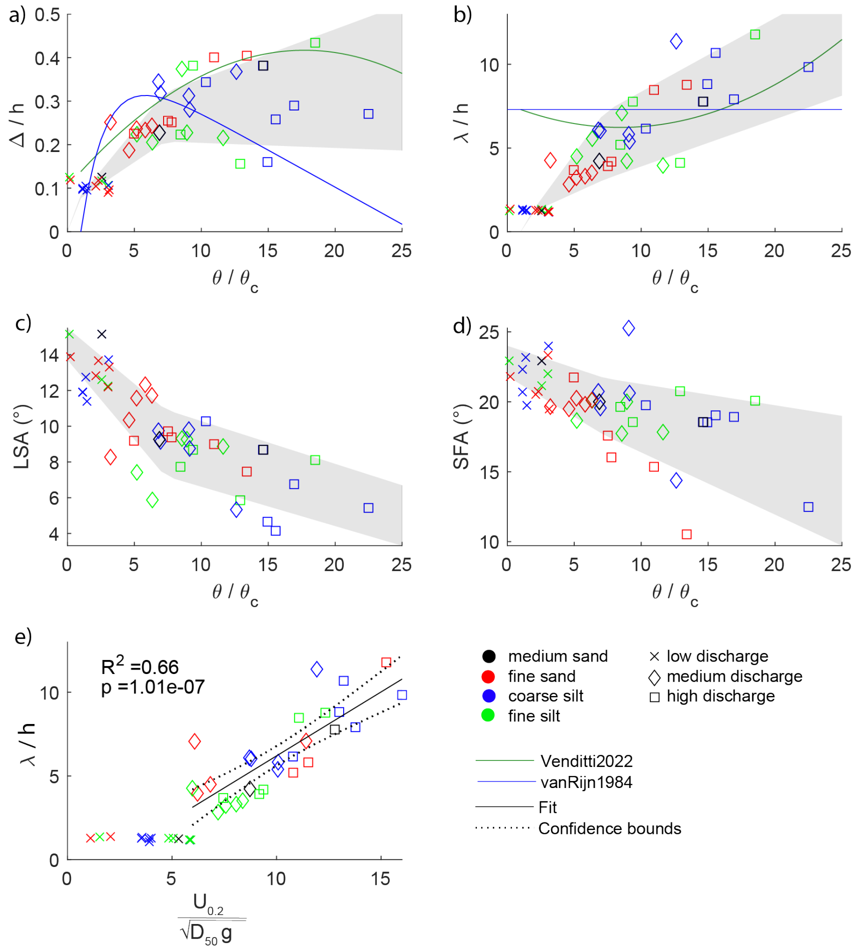

Figure 9. Increasing variability in bedform geometry with increasing flow strength, expressed as transport stage (θ/θ_c) in (a-d) and as non-dimensionalized velocity at 20% above the bed in (e). a) Bedform height divided by water depth. b) Bedform length divided by water depth. c) Leeside angle. d) Slip-face angle. e) Bedform length divided by water depth. Grey shading indicates one standard deviation from the mean value, in which the standard deviation is calculated from all bedforms in either low, medium or high discharge experiments. The base runs are indicated with black markers (medium sand). In (a) and (b), the predicted values by Venditti and Bradley (2022) and Van Rijn (1984) are shown.

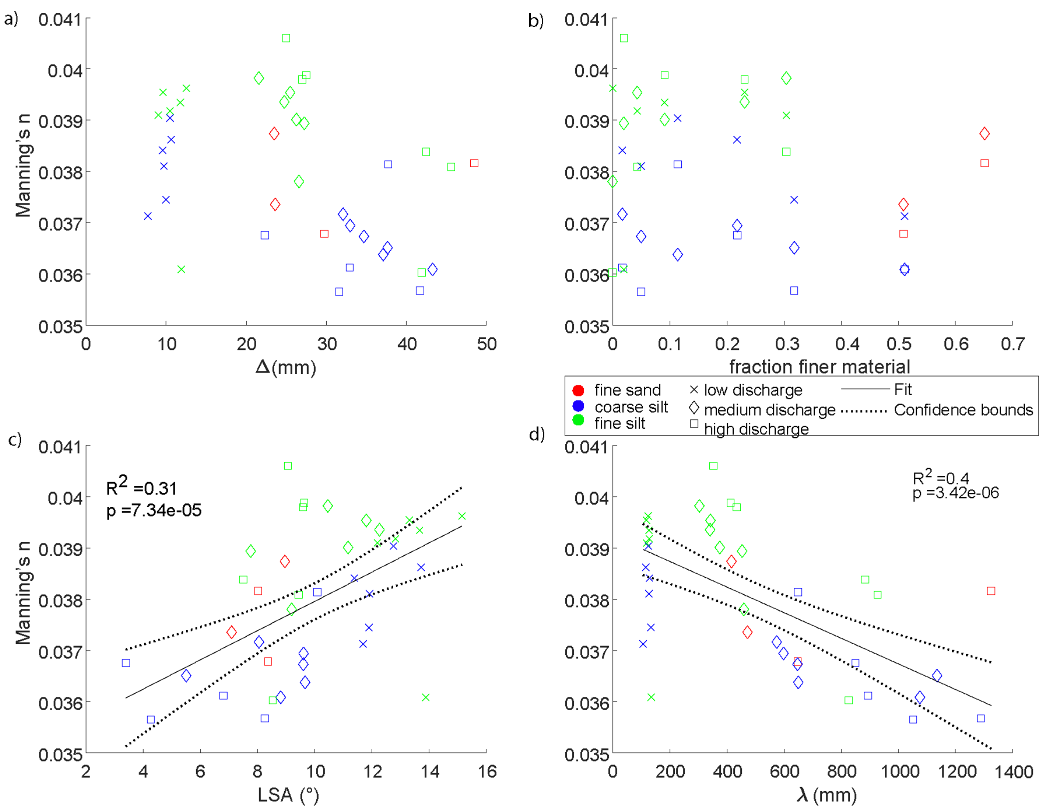

Figure 10. The relation between the hydraulic roughness n_{man}, calculated with the Law of the Wall, and a) Bedform height, Δ. b) Fraction finer material within the base material. c) Leeside angle, LSA. d) Bedform length, λ. Significant linear relations are shown in c and d.

Counter-intuitively, hydraulic roughness does not exhibit a statistically significant relationship with dune height and the fraction of added finer material (Figure 10a-b). The lack of a relationship with added fine material is consistent with the roughness predictor of Van Rijn (1984), which differentiates between skin friction, related to grain size, and form friction, related to bedform size. According to this predictor, on average, 97% of the total amount of friction is attributed to form friction in the experiments, indicating that bed composition is less important for hydraulic roughness than bedform geometry. The roughness predictor of Van Rijn (1984) yields on average a Manning's n of 0.030, which is 11% lower than the measured friction based on the Law of the Wall.

4 Discussion

4.1 A shift in transport stage due to addition of fines

The transport stage-based dune height predictor of Venditti and Bradley (2022) provides a way to visualize the experimental results and assess deviations from expected heights caused by the sediment mixtures (Figure 11). The predictor implies a parabolic relationship between bedform height and transport stage, as well as confidence levels for data variability (Bradley and Venditti, 2017). The parabolic relation can be interpreted as follows. As the transport stage increases, the transport mode changes from bed load to mixed load (w_s / u^* decreases), and dune height increases. This corresponds to our low and medium-discharge experiments. As the transport stage increases further, bedforms start to become washed-out, thus reducing the bedform height. This corresponds to our high-discharge experiments (Yalin, 1972; Naqshband et al., 2014).

Although this framework is generally associated with a change in flow strength (Shields number, θ), it can also be used to frame the experimental data using changes in sediment mobility (critical Shields number, θ_c) caused by the addition of fine material to a coarser base sediment (Figure 11). During the medium-discharge experiments, adding non-cohesive fine sand and coarse silt led to an increase in dune height and length. When comparing this to the expected change based on the predictor of Venditti and Bradley (2022) due to a decrease in D_{50} resulting from the addition of fine sediment, the change in bedform geometry was larger than expected. We attribute the increase in bedform size to an increase in mobility of the bed material (i.e. a decrease in θ_c), leading to a larger change in transport stage (Section 4.2) than expected based on the change in D_{50} (Supplementary Table S1). Therefore, adding fine, non-cohesive material leads to a shift to the right on the bedform height - transport stage diagram (Figure 11). In contrast, adding fine, weakly cohesive material to the bed decreases the mobility of the sediment (Section 4.3), and therefore decreases the transport stage, resulting in a decrease in bedform size, leading to a shift to the left on the diagram in Figure 11. Furthermore, the large variability in bedform geometry at the high transport stages is attributed to instabilities that occur when the system moves towards upper-stage plane bed (Section 4.4). Finally, the ripples formed at low discharge do not fit within the transport stage diagram, since ripple size is only dependent on grain size and not on flow velocity (Baas, 1994; Baas, 1999; Soulsby et al., 2012). Below, these changes are discussed in more detail.

4.2 Impact of non-cohesive fine sediment (sand and coarse silt)

4.2.1 Hiding-exposure effect

During the medium-discharge experiments, we observed an increase in dune size with larger fractions of fine non-cohesive material (fine sand and coarse silt) mixed into the base material. This may be attributed to an increased mobility of the coarse sediment. In mixed sediments, differently sized grains interact with the flow and with each other in a different way than in equally sized sediments (McCarron et al., 2019), leading to selective entertainment. This is called the hiding-exposure effect, where small grains are hidden

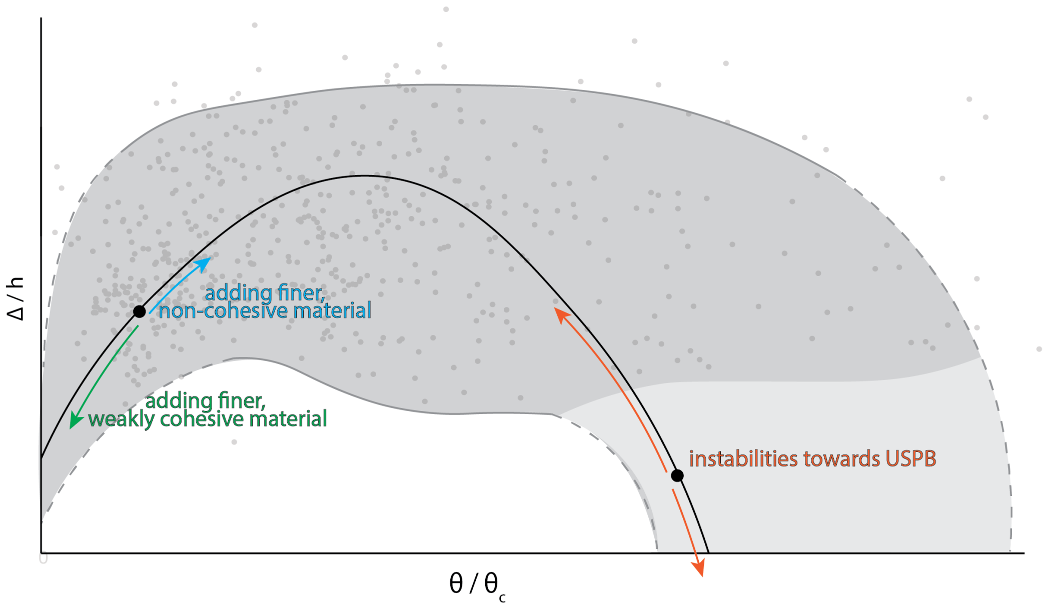

Figure 11. Conceptual diagram of non-dimensionalized dune height against transport stage, indicating the impact of adding non-cohesive and cohesive fine sediment to the bed material at relatively low transport stages, and the increased variability of bedform height due to flow instabilities at high transport stages. The dark grey shading indicates the 5 and 95-percentiles of data aggregated from Venditti et al. (2016) and Bradley and Venditti (2019). No data are available for the light grey shaded area. The dashed lines show the estimated course of the confidence intervals.

from the flow between the coarser grains. This does not only result in a more difficult mobilization of the fines (hiding), but also in an increased mobility of the larger grains (exposure) (Einstein, 1950) (see Section 4.2.2).

The hiding-exposure effect is mostly dependent on the ratio between the fraction of interest D_i (here, the coarse fraction) and the D_{50}. Hill et al. (2017) tested the influence of this ratio for gravel-sand mixtures. They found that if the two mixed sediments had similar grain sizes, (D_{coarse} / $D_{fines} < 2$), the bed aggregated without preferentially mobilizing the coarser fraction, and the fines became part of the bed structure (Frings et al., 2008). For intermediate particle ratios ($2 < D_{coarse}$ / $D_{fines} < 20$), the fine sediment filled or bridged the pores of the coarser base matrix, resulting in increased mobility of the coarse fraction (Section 4.2.2). For large ratios (D_{coarse} / $D_{fines} > 20$), the fine sediment percolated through the base sediment. The subsurface became clogged, but the fines were not present in the surface layer, because all free fines were entrained and transported in suspension.

In the present experiments, the ratios between the coarse and fine fractions were 1.5, 6.9 and 15 for fine sand, coarse silt and fine silt, respectively. Following Hill et al. (2017), this implies that the fine sand aggregated the bed structure, whereas the coarse and fine silt bridged or filled the pores of the coarse fraction. For the silts, the hiding-exposure effect should have played a role, increasing the mobility of the coarse fraction, whereas, for the fine sand, the increased size distribution might have resulted in increased mobility of the entire sediment bed due to an increase in grain protrusion and a decreased friction angle (Kirchner et al., 1990; Buffington et al., 1992). However, this effect may have been smaller than the mobility increase caused by the hiding-exposure effect by coarse silt, which is indicated by the increased lengthening of dunes in a bed with coarse silt compared to fine sand. Increased mobility means an increased transport stage, hence an increased dune length (Section 4.1).

Various methods have been developed to correct the initiation of motion of sediments for the hiding-exposure effect (see McCarron et al. (2019) for a review). Generally, the correction factor lowers the critical Shields number, θ_c, for the coarse fraction ($D_i > D_{50}$), and increases it for the fine fraction ($D_i < D_{50}$). The correction factor, ζ, commonly takes this form (Einstein, 1950; Wilcock, 1993):

$$\zeta = \alpha \left(\frac{D_i}{D_{50}} \right)^{-\beta} \tag{15}$$

where D_i is the grain size of the fraction of interest, β controls the strength of the hiding-exposure effect (Buffington and Montgomery, 1997; McCarron et al., 2019), and $\alpha =$ 1 for sediments with the same density. Exponent β has been approximated using σ_g, as a measure for sorting (Patel et al., 2013; McCarron et al., 2019): $\beta = 0.96$ for $\sigma_g < 2.85$ and $\beta = 2.67\mathrm{e}^{-0.37\sigma_g}$ for $\sigma_g \geq 2.85$, where σ_g is determined with equation (4).

Applying this correction factor to the experimental data shows that adding a larger fraction of fine material results in a larger increase in mobility of the coarse material. For example, replacing 50% of the base material by fine sand causes θ_c of the base material to decrease from 0.021 to 0.019 (-11%) and to 0.016 for 50% coarse silt (-31%) (Supplementary Table S1). Applying this adjusted critical Shields number to our data reduces the root-mean-square error of the observed normalized dune height by 0.019 (-9%) and 0.032 (-15%) for fine sand and coarse silt, respectively, when evaluated against the predictor of Venditti and Bradley (2022). In contrast, the same adjustment increases the root-mean-square error for the experiments with fine silt by 0.011 (+6%) and causes the variability for the high discharge runs to remain high, with a root-mean-square error of 0.31. These results are discussed in Sections 4.3 and 4.4, respectively.

4.2.2 The hiding-exposure effect in mixed gravel-sand and sand-silt beds

The hiding-exposure effect is not commonly recognized in studies focused on sand-silt mixtures, and is mainly based on experiments in gravel-sand mixtures. McCarron et al. (2019) described an increase in mobility in gravel-sand experiments based on a decrease in θ_c by 64% compared to well-sorted sediment of a similar size (2.14 mm). Frings et al. (2008) speculated that hiding-exposure could result in a more mobile coarse fraction than a fine fraction in the downstream part of sand-bed rivers. Our observations with sand-silt mixtures show many parallels to gravel-sand mixtures, but on a smaller grain-size scale. We therefore infer from our experiments that the hiding-exposure effect also plays a role in sand-silt mixtures.

Mechanisms explaining the increased mobility of gravel in sand-gravel mixtures were suggested by Ikeda (1984) and subsequently built on in later studies (e.g. Li and Komar 1986; Whiting et al. 1988; Dietrich et al. 1989; Wilcock 1993; Venditti et al. 2010). Firstly, by filling pores with fine grains, the pivoting angle of large grains is reduced, thus facilitating entrainment (Li and Komar, 1986). Secondly, there is a lower probability that particles in transport are caught in the wake of protruding particles and deposit, since particles protrude less far into the flow. Finally, filling pores with fine material results in a smoother bed, thus resulting in lower drag, which in turn increases the near-bed velocity. These suggestions were built upon by Venditti et al. (2010), who suggested that the infilling of the pores causes dampening of small wakes in the lee of particles, resulting in acceleration of the near-bed flow, which in turn mobilizes the larger particles. Our experimental results suggest that this acceleration of near-bed velocity is reflected in an increase in dune length and height at medium discharge (Figure 9d).

The observation that the sediment mobility increases when adding coarse silt to the bed is in line with what can be expected from experiments with gravel-sand mixtures, but opposes previous observations in laboratory experiments with sand-silt mixtures. Bartzke et al. (2013) and Yao et al. (2022) observed that non-cohesive silt stabilizes the sediment bed, but at different concentrations (∼1.4% silt and >35%, respectively), whereas, in our experiments, even at 50% coarse silt the mobility of the sediment was increased. Interestingly, Bartzke et al. (2013), whose experiments fall in the range of pore bridging (D_{coarse} / D_{fines} = 5.5), explained the filling of pore space as a reason for increased stability of the bed due to reduced hyporheic flow, rather than a reason for increased mobility of the coarse fraction as found in gravel-sand experiments (Section 4.2.1). The reason for these opposing effects could lie in the different experimental setups: the highest flow velocity tested in these experiments was 0.35 m s^{-1}, which is comparable to our lowest flow velocity. It is therefore likely that the supposed stabilizing effect of silt is overruled by a large bed shear stress and the development of bedforms in our experiments.

Ma et al. (2020) studied the mobility of silt-sized sediment and the effects of sorting in laboratories and rivers world-wide, and found a high-mobility sediment transport regime related to the size and sorting of the bed sediment. Bed sediments of $D_{50} < 88$ μm and poorly sorted sediments within a range of 88 μm < D_{50} < 153 μm were found to be more mobile than expected from the sediment transport rate equations of Engelund and Hansen (1967), whereas sediments with $D_{50} > 153$ μm confirmed these equations. In other words, poorly sorted sediments in the transitional range of very fine to fine sand are more easily mobilized than narrowly distributed sediments. This agrees with equation (15), where the strength of the hiding-exposure effect is related to the sorting of the material. Although Ma et al. (2020) did not explicitly mention the hiding-exposure effect, and related their observation to the change from mixed load to suspended-load dominated transport, the hiding-exposure effect may have played a role to achieve this change.

4.3 Impact of weakly cohesive fine silt

Contrary to the increase in mobility observed when adding non-cohesive fine material, the mixing of fine silt into the bed reduced both the height and length of the bedforms. This can be attributed to the weakly cohesive character of the 17 μm-sized silt, because cohesive sediments such as clay are known to limit or suppress bedform growth (Schindler et al., 2015; Parsons et al., 2016) through London-van der Waals forces and by interparticle electrostatic bonding (Mehta, 2014), consequently increasing θ_c.

The fine silt used in our experiments exhibited weakly cohesive properties, confirmed by visual stickiness of slurries of the fine silt and an increased angle of repose. Therefore, fine silt might have imparted similar attractive forces as clay, although to a lesser extent. Schindler et al. (2015) and Parsons et al. (2016) performed experiments with fine sand (D_{50} = 239 μm) at a mean velocity $u = 0.8$ m s^{-1}, and observed an inverse linear relationship between dune height and clay percentage, with a lack of dunes at a clay percentage of 15%. The sharp decline in bedform height with clay content as observed in their experiments, was not evident in the present experiments, and the bed remained mobile up to 30% fine silt. Nevertheless, in the medium-discharge experiments, the dune heights and lengths for fine silt were significantly reduced, as opposed to the increase for coarse silt and fine sand, likely due to decreased mobility of the entire bed. In the low-discharge experiments, the ripple size was reduced too, but, as shown below, this could be a result of decreased grain size rather than decreased mobility.

Wu et al. (2022) recorded a decrease in ripple height with increasing clay percentage under wave-current conditions (D_{coarse} / $D_{fines} \sim 51$). Below 11% clay, the clay was winnowed out of the bed, allowing clean-sand ripples of similar size to develop. Above 11%, the cohesiveness of the bed was large enough to limit bed mobility, and only small ripples formed. In our experiments, this effect did not occur, as even at small percentages of fine silt ($\sim$ 2%) bedform height decreased, as in the current-ripple experiments with mixed clay-sand of Baas et al. (2013). During the medium-discharge experiments, cohesion impeded dune formation, and only small bedforms formed. In the high-discharge experiments, dunes did form, but their planform was more similar to the dunes formed in the medium-discharge experiments with fine sand and coarse silt than to those in the high-discharge runs (Supplementary Figure S2 and S3), indicating cohesion-induced hampered mobility.

In summary, the formation of relatively small bedforms in our experiments with fine silt can be attributed to reduced mobility, caused by the weakly cohesive properties of fine silt. This effect is less pronounced than in previous experiments with more strongly cohesive clay, in which the mobility was limited more strongly. The decreased mobility leads to an increase in the critical Shields number, and a shift to the left in the transport-stage diagram of Figure 11.

4.4 Instabilities at high discharges

The present study shows that any impact of fine sediment on bed geometry at high transport stages is swamped by the inherent variability of dune geometry (Figure 11). This variability encompasses three bed configurations, without any apparent relationship with the type or fraction of fines: a dune-covered bed; a flat bed with one large dune (cf. Saunderson and Lockett (1983) and Naqshband et al. (2016)); and a completely flat bed.

The variability in bedform geometry and the presence of multiple bed configurations have been described before in literature. Saunderson and Lockett (1983) performed experiments around the transition from dunes to upper-stage plane bed and found four different bed states: asymmetrical dunes; convex dunes; humpback dunes (comparable to the single large dune configuration in this study); and a flat bed. These bedform states were seen to transform into one another. Saunderson and Lockett (1983) dedicated this behavior to the close position of the bed to the phase boundary between dunes and upper-stage plane bed, but did not provide a physical explanation. Venditti et al. (2016) observed three phases in high-velocity experiments: a plane bed with washed-out dunes; a field of large dunes; and a field of small dunes. The water depth, shear stresses and water surface slope co-varied with the changes in bed configuration. During the plane-bed phase, intense localized erosion was followed by the formation of small or large bedforms, which then washed out to form a new flat bed. These cycles lasted from several minutes to more than half an hour, with transitions between individual bedform types happening in seconds or minutes. Similarly, Bradley and Venditti (2019) stated a 'tremendous variability' between bed states at a high transport stage, and reasoned that numerous observations of the bed are needed to get an average bed state that scales with the transport states described by equations (8) and (9).

However, none of these studies provided an explanation for the large variability in dune height at high transport stages. de Lange et al. (2023) reanalyzed the data of Venditti et al. (2016) and Bradley and Venditti (2019), and found a bimodal dune height distribution at high transport stages. They attributed this to a critical transition, exhibiting flickering between a high and low alternative stable state. Our current observations support the idea of these alternative stable states. The large variability in bed configurations explains the lack of a predictable succession of bed states with increasing amounts of fine sediment in the current study. This variability is so large that all bed states can occur at any moment, independent of the bed composition. However, the upper stage plane bed condition was not observed in the high-discharge experiments with fine silt, which once again shows a decreased mobility as a result of the cohesiveness of the sediment, leading to a shift to the left on the bedform-transport stage diagram, preventing flattening of the bed.

4.5 Ripples at low discharges

Ripples formed in the low discharge experiments. Ripple height and length are a product of the size of the bed material, and are independent of flow velocity (Baas, 1994; Baas, 1999; Soulsby et al., 2012). Therefore, the transport stage framework as suggested above for dunes is not relevant for ripples. The height and width of the ripples, and to a lesser degree their length, decreased with an increasing amount of coarse and fine silt. The decrease in height is most apparent at silt concentrations above 20%, the same percentage at which the D_{10} of the sediment distribution drops considerably (Figure 3).

Adding fine sand to the base material led to a decrease in height of about 15%, a similar decrease as expected based on Soulsby's ripple predictor (equation (10)). This suggests that the change in grain size dominated the change in ripple height, and the hiding-exposure effect was small. However, adding coarse silt to the base material had a larger decreasing effect on height and length than fine sand. In the run with 50% coarse silt, both the height and the length were at, or close to the predicted values of 8 mm and 95 mm, respectively, suggesting that equilibrium was reached in this run. Hence, adding coarse silt increases the development rate of the ripples compared to fine sand. This may be caused by three processes; a) a mobility increase induced by the hiding-exposure effect; b) a shorter equilibrium time for coarse silt ripples at the same Shields stress; c) a larger relative effect of coarse silt than fine sand, as a 50% increase in weight of the finer fraction involves a much larger number of coarse silt than fine sand particles (in the same volume, there are 331 times more coarse silt particles than medium sand particles, as opposed to 3 times for fine sand). Finally, adding fine silt to the base material shows the effect of cohesion by reducing the ripple height. However, the effect of particle size cannot be distinguished with confidence from that of cohesion. The decrease in ripple height with increasing fraction of fine silt is larger than for coarse sand, which might be at least partly caused by the cohesive properties of the fine silt.

It should be emphasized that the response of ripples to an increase of fine bed sediment is different from the response of dunes. Whereas dune geometry gets adjusted by the increased mobility of the non-cohesive bed sediment, ripple geometry mainly results directly from the particle size distribution of the material.

4.6 The impact of bed sediment on hydraulic roughness

We confirm that for relatively steep dunes, roughness is related to the steepness of the leeside, consistent with findings of Kwoll et al. (2016) and Lefebvre and Winter (2016). At the leeside of the dune, flow separation generates turbulence, resulting in energy dissipation in the turbulent wake, which constitutes the main source of dune-related roughness (Lefebvre et al., 2014; Venditti and Bennett, 2000). In our experiments, the bedforms had on average a leeside angle of 10° with a relatively steep section (mean slip-face angle 20°), resulting in intermittent flow separation (Lefebvre and Cisneros, 2023). The presence of flow separation can also be determined using the defect Reynolds number (Baas and Best, 2000), Re_d ($Re_d = \frac{\Delta u^*}{\nu}$). In all our experiments, Re_d is far larger than 4.5, which indicates the presence of flow separation (Williams and Kemp, 1971; Best and Bridge, 1992; Gyr and Müller, 1996).

Previous research suggested that the composition of the sediment bed has only a small influence on hydraulic roughness (Smith and McLean, 1977). This corresponds with our findings and equation (13) as far as skin friction is concerned; only 3% of the total roughness is attributed to skin friction in the present experiments. However, the bed composition strongly impacts the bed geometry, thereby influencing form roughness.

4.7 Wider implications

Our results show that the presence of fines affects sediment mobility, even if the fines only slightly change the D_{50} of the sediment. Therewith, fine material influences bedform properties and hydraulic roughness, which is worth accounting for in bedform size predictors. Moreover, the interaction of fine silt and sand with coarser sand is relevant for channel nourishment aimed at preventing incision (Czapiga et al., 2022).

To adequately determine bedform geometry, some measure of bimodality or sorting may be included in future predictors. This measure could focus on the fine fraction, such as the D_{10}. Additionally, the bed geometries for added fine and coarse silt differ notably, if the fine silt fraction is cohesive. Hence, assessing the cohesive properties of silt, such as yield stress and viscosity, is crucial, and lumping fines into one fraction, with a cut-off at 63 μm (e.g. Rijn (2020)) is to be avoided.

5 Conclusions

We performed 52 laboratory experiments, in which the bed composition was varied using three different sediment mixtures (medium sand with fine sand, coarse silt and fine silt) in different ratios, for three different discharges (low, medium, high). We measured the bed morphology at the end of the experiments to assess the effect of bed composition on bedform geometry, and used this to indirectly assess sediment mobility and transport stage. The main conclusions of the research are:

- Bedform response to the addition of fine material depends, amongst others, on transport capacity, bimodality-impacted bed mobility, and cohesion.
- In the dune regime, adding fine sand or coarse silt to medium sand increases the mobility of coarser material. This leads to an increase in transport stage, θ/θ_c, an increase in dune length, and an increase or decrease in dune height, depending on the initial value of θ/θ_c.
- The increase in mobility of medium sand is inferred to be caused by the hiding-exposure effect, with the filling of pores by coarse silt leading to a larger near-bed flow velocity. Fine sand is too coarse to fit in the pores, which causes an increase in grain protrusion and a decrease in friction angle, and therefore increased sediment mobility.
- Adding weakly cohesive fine silt to medium sand has a similar effect to adding cohesive clay (Schindler et al., 2015), by causing a decrease in transport stage and inhibiting dune growth.
- In the ripple regime, adding fine material leads to a decrease in ripple height, which responds directly to the decreased particle size.
- In the transitional regime from dune to upper-stage plane bed, bed geometries may flicker between alternative stable bed states, complicating the relation between bedform height and length and fine sediment fraction.
- The composition of the sediment bed does not significantly influence hydraulic roughness from skin friction drag, but it alters the bed morphology, and thus indirectly changes the hydraulic roughness through form drag.

Appendix A Bedform geometry predictors

The dune height and length predictions based on Van Rijn (1984) follow equation (6) and (7) in which T is Van Rijn (1984)'s definition of the transport stage.

$$T_{vRijn} = \frac{(u^*)^2 - (u_c^*)^2}{(u_c^*)^2} \tag{A1}$$

where u^* is the shear velocity (m s^{-1}), and u_c^* is the critical shear velocity (m s^{-1}). Both the shear velocity and the critical shear velocity are unknown, but can be expressed in known parameters. The shear velocity can be expressed via:

$$u^* = u\frac{g^{0.5}}{C'} \tag{A2}$$

in which u is the time and depth-averaged velocity (m s^{-1}) derived from the measurements with the UB-LAB 2C and *C'* is the grain-related Chézy parameter (m$^{0.5}$ s^{-1}), which can be expressed as:

$$C' = 18log\frac{12R_h}{3D_{90}} \tag{A3}$$

Herein, R_h is the hydraulic radius, which is equal to the cross-sectional area (A) divided by the wetted perimeter (P = width + $2h$) .

The critical shear velocity can be calculated as:

$$u_c^* = \sqrt{\frac{\tau_c}{\rho_w}} \tag{A4}$$

In turn, the critical shear stress can calculated using the critical Shields number θ_c:

$$\tau_c = \theta_c(\rho_s - \rho_w)gD_{50} \tag{A5}$$

and θ_c is obtained from (Parker et al., 2003):

$$\theta_c = 0.5\left(0.22Re_p^{-0.6} + 0.06 * 10^{(-7.7Re_p^{-0.6})}\right) \tag{A6}$$

In which the particle Reynolds number, Re_p (-), is defined as:

$$Re_p = D_{50}^{3/2}\frac{\sqrt{\rho_r g}}{\nu} \tag{A7}$$

Venditti and Bradley (2022)'s empirical equation for predicting dune height and length can be found in equation (8) and (9). The dimensionless shear stress θ is derived by calculating the shear stress τ from the shear velocity (via equation (A4), replacing τ for τ_c). The critical shear stress θ_c is calculated via equation (A6).

The geometry of ripples is predicted based on Soulsby et al. (2012) via equation (10) and (11) in which D^* (-) is given by:

$$D^* = D_{50}\left(\frac{g(\frac{\rho_s}{\rho_w} - 1)}{\nu^2}\right)^{1/3} \tag{A8}$$

Appendix B Hydraulic roughness determination

For a water column that satisfies equation (12), the equation can be rewritten into:

$$\overline{u}(\sigma_d) = \frac{u^*}{\kappa}(ln(\sigma_d) + 1) + U \tag{B1}$$

in which U is the depth-mean velocity, and σ_d is the dimensionless depth using:

$$\sigma_d = \frac{z + h}{h} \tag{B2}$$

The value of u^* can be derived from the slope of a linear regression line through the data points of $\overline{u}$ versus (ln(σ_d)+1). The average velocity $\overline{u}(\sigma_d)$ was determined as the average streamwise velocity during a single measurement. The averaging time window of 30 minutes was narrowed down to cover an integer number of bedforms, defined from top to top. The σ_d-coordinate was defined such that σ_d=0 coincides with the top of the highest bedform during a measurement (the 95-percentile of the measured bed elevation was chosen, to exclude outliers as a result of backscatter spikes). The σ_d=1-coordinate is located at the top of the vertical measuring range, which corresponds to the elevation of the UB-Lab-2C transducer. The time-averaged relation between $\overline{u}$ and $ln(\sigma_d)$ was consistently linear at the middle half of the measured profile (between -0.175 < σ_d < -0.625), so this part of the profile was used for determining u^* (Supplementary Figure S6). The goodness of the linear fit of the log-profiles had on average a R^2-value of 0.96. Following Hoitink et al. (2009), the roughness length z_0 (m) can be calculated using:

$$z_0 = \frac{h}{e^{\left(\frac{\kappa U}{u^*}\right)} + 1} \tag{B3}$$

Finally, Manning's n, n_{man} (s m$^{-1/3}$) can be calculated in the following steps (Pope, 2000; Chow, 1959):

$$k_b = 30 * z_0 \tag{B4}$$

$$n_{man} = \frac{k_b^{\frac{1}{6}}}{25} \tag{B5}$$

in which k_b is the total roughness height (m).

Roughness height can also be approximated indirectly based on the predictor of Van Rijn (1984) with equation (13), resulting in the dimensionless Darcy-Weisbach friction factor, $\hat{f}$. Herein, k_s consists of form roughness height k_{sf} and grain roughness height k_{sg}:

$$k_s = k_{sg} + k_{sf} \tag{B6}$$

$$k_{sg} = 3D_{90} \tag{B7}$$

$$k_{sf} = 1.1\gamma_d\Delta(1 - e^{\frac{-25\Delta}{\lambda}}) \tag{B8}$$

where the calibration constant γ_d is taken as 1 in laboratory conditions (Van Rijn, 1984).

The friction factor, $\hat{f}$, can be converted to Manning's n (n_{man}) via the Chézy coefficient C (m$^{1/2}s^{-1}$) (Manning, 1891; Silberman et al., 1963).

$$C = \frac{R_h^{1/6}}{n_{man}} \tag{B9}$$

$$\hat{f} = \frac{8g}{C^2} \tag{B10}$$

Open Research Section

The data and code used to generate the results in this study will be made available through the public repository of 4TU upon acceptance, with doi: 10.4121/dde430c4-7f9f-4d7b-bff1-d4792e0031f2.

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