Uniform and graded bed-load sediment transport in a degrading channel with non-equilibrium conditions

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ABSTRACT

Bed-load transport plays a critical role in river morphological change and has an important impact on river ecology. Although there is good understanding of the role of the variation of river bed grain size on transport dynamics in equilibrium conditions, much less is understood for non-equilibrium conditions when the channel is either aggrading or degrading. In particular, the relative role of different grain sizes in the promotion and hindering of the transport of coarse and fine fractions in a degrading channel has yet to be investigated. The current study attempts to provide new understanding through a series of flume experiments done using uniform and graded sediment particles. The experiments revealed coarser grain-size fractions for a poorly-sorted sediment, relative to uniform-sized sediment, reduced the transport of finer grains and finer fractions enhanced the transport of coarse grains. This hindering-promotion effect, caused by relative hiding and exposure of finer and coarse fractions, increased with bed slope and decreased with relative submergence. In particular, as relative submergence increased, the graded fractions tended towards behaving more like their uniform-sized counterparts. Also, the bed-load parameter of the graded fractions increased more with a rise in bed slope than observed for the uniform-sized counterparts. These results revealed, for degrading channel conditions, such as downstream of a dam, bed-load equations developed for uniform bed sediment are inappropriate for use in natural river systems, particularly in mountain streams. Furthermore, changes in river

bed composition due to activities that enhance the input of hill-slope sediment, such as fire, logging, and agricultural development, are likely to cause significant changes in river morphology.

Keywords: Graded sediment, Exposure, Hiding, Flume Experiments, Non-equilibrium.

1. Introduction

Coarse sediment transport in streams is responsible for shaping channel morphology and controlling morphodynamics (Baewert & Morche, 2014; Liébault et al., 2016). Accurate quantification of morphodynamic processes is needed for assessment of hazards along river corridors, such as flooding and pollutant transport, and for defining water and land management plans that mitigate their impact (Chien & Wan, 1999; Frey & Church, 2009; Graf, 1971; Raven et al., 2010; Wilcock, 1998). Although traditional bed-load equations are often used for practical reasons (e.g., Engelund & Hansen, 1967; Meyer-Peter & Muller, 1948), most of them have been developed based on laboratory data, collected under simplified conditions and using uniform bed sediment (Li et al., 2016). Uncertainties in predictions when using these traditional formulas are in the range of orders of magnitude. Thus, bed-load assessment in rivers and streams is still one of the major challenges facing fluvial hydraulics and river engineers, especially in channels with heterogeneous sediment (Bagnold, 1977).

The mobility of sediment in high gradient rivers is significantly affected by grain sorting (Hammond et al., 1984), hiding-protrusion effects (Ashworth & Ferguson, 1989), low relative roughness (Bathurst et al., 1983), presence of an armor layer (Lenzi, 2004), and slope (Lamb et al., 2008). Traditionally the movement of a single particle from a uniform bed in any flow can be determined by flow velocity, sediment size, and sediment density (Allen, 1985; Leeder, 1982), but in graded sediment there is a non-negligible inter-granular effect that must be considered. As bed-load field measurements are often difficult to make in a range of flow and channel conditions, flume experiments have long been a very powerful tool for exploring the process of bed-load transport (Howard, 2008).

A large body of research has attempted to investigate these processes in graded channels under equilibrium conditions (Kuhnle, 1993; Kuhnle, 1996; Kuhnle et al., 2013; Wilcock & Crowe, 2003; Wilcock & Kenworthy, 2002; Wilcock et al., 2001; Wilcock & McArdell, 1993). Along with field-gathered data, this approach has led to the development of bedload equations for graded sediment (e.g., Almedeij et al., 2006; Patel & Ranga Raju, 1996; Wilcock & Crowe, 2003; Wilcock & Kenworthy, 2002; Wu, 2004). However, non-equilibrium conditions, when the channel is either aggrading or degrading, are more difficult to study. For aggrading conditions a number of models are available (Belleudy & Sogreah, 2000; Cui, 2007; Cui et al., 1996; Hu et al., 2014; Qian et al., 2015; Wu &Wang, 2008), but in the case of degrading channels, such as downstream of a dam, only a few computational models are available because experimental data often is insufficient to produce models that perform well over a range of flow and channel conditions (e.g., Dietrich et al., 1989; Fuller, 1998; Pender et al., 2001; Willetts et al., 1998). In a degrading channel, Li et al. (2016) showed that sand greatly promotes the transport of gravel, whilst gravel significantly reduces the transport of sand, as others observed for equilibrium conditions (e.g., Venditti et al., 2010; Wilcock & McArdell, 1997; Wilcock et al., 2001; Wilcock & Crowe, 2003). However, the relative role of different grain sizes in this promotion and hindering effect has yet to be investigated. For example, although Li et al. (2016) investigated the promotion and hindering effect of uniform sand and gravel, no study in degrading channels has considered how the mobility of grain size fractions of graded sediment differ from their counterpart uniform-sized sediment. Nor has any study examined how this difference between graded and uniform-sized sediment varies with key channel conditions, such as bed slope and relative submergence. Such information would provide new understanding on why promotion and hindering occur for graded sediment. The current study attempts to provide this new understanding.

The current paper presents a series of laboratory flume experiments done using uniform and graded sediment, designed to shed further light on the fractional bed-load sediment transport rate for poorly-sorted beds in degrading channel conditions. The main goals are to compare transport rates of uniform and poorly-sorted sediment and their variation with bed slope and relative submergence under degrading conditions. In particular, the study aims to determine the mobility of different graded fractions in comparison to counterpart uniform-sized sediment, and the effect of fine fractions on the total transport rate of graded sediment. The current research offers insight into the significance of grain size variation in governing the transport of coarse-grained river beds.

2. Experimental methods

2.1. Experimental procedure

A total of 86 experiments were done in a 12-m long, 0.5-m wide, and 0.5-m deep rectangular glass-wall flume channel with an adjustable slope in which water was recirculated (Fig. 1). Four naturally rounded groups of uniform sediment particles of mean size 5.17, 10.35, 14, and 20.7 mm were used; along with a graded sediment mixture obtained using the four uniform sizes mixed with equal proportions in weight (Table 1).

Fig.1.

Table 1.

The slopes used in the experimental runs varied from 0.005 to 0.035 m/m depending on the grain sizes used (Table 2). Nets were installed at the upstream end of the flume to straighten and smooth the flow into the channel. The first 4 m and the last 2.8 m contained fixed bed sections that were artificially roughened to prevent local scour and back-water effects (see Fig.1). In between, the flume was filled with mobile sediment particles.

Table 2.

These mobile sediment particles were level flat to a depth of ~ 5-6 d_{50} (where d_{50} is the median particle size). These sediment particle were re-screeded and completely re-mixed (for graded sediment) after each run. A 0.5 m x 0.2 m trap was used to collect the transported sediment at the downstream end of the flume. Whenever the trap was filled, another trap was immediately substituted. The flow was controlled using a tailgate at the downstream end of the flume and the water depth was measured using two moving point gauges and three ultrasonic sensors operating at 25 Hz (see Fig.1). The first ultrasonic sensor was positioned in the upstream fixed bed section and the second and third in the movable bed section. The first and second point gauges were located in the first and last parts of the movable bed.

Prior to each experiment, the slope of the flume was set, the tailgate was raised, the flume was slowly filled with water at the downstream end to prevent disruption of the initial bed, the pump was turned on, and the inlet valve and tailgate slowly opened to create a low, steady initial flow condition. This initial inflow was set such that no sediment transport took place. Finally, the flow was gradually increased to the desired value and held constant. Uniform flow was then established by adjusting the tailgate and sediment transport sampling began. The duration of each run depended on the sediment transport rate, the larger transport rate, the shorter the duration, which varied between 1 to 30 min, and the duration of bed-load sampling was several seconds to several minutes. This sampling allowed the temporal change in the transport rate and transported bed-load composition to be determined. The bed slope, flow velocity flow depth, and sediment transport rate were measured continuously during all experimental runs. Mean flow velocity was estimated using the travel time of a tracer (potassium permanganate). Due to the short duration of the experiments, no sediment feeding was done. The effect of not-feeding sediment in the short duration experiments, only affected the upstream-end of the channel, and did not affect the morphology in the downstream sections of the stream nor the sediment transport rates determined at the channel outline (Binns & Da Silva, 2009). Thus, all experiments were done for a degrading bed. All flows were fully turbulent and supercritical except for tests 1 and 2 in which the Froude number, Fr, was 0.97 and 1, respectively (Table 2).

The flume experiments were designed to test the influence of bed slope and relative submergence on the sediment transport rate, bed-load composition, and mobility of the uniform-sized and graded bed sediment. Relative submergence was defined as $RS = y/d$, where y is the flow depth and d is the bed grain size (equal to the mean particle diameter for uniform sediment and d_{50} for graded sediment). To determine the impact of bed slope, runs were done in which the flow depth was held constant and the bed slope was increased, meaning that the discharge, shear stress, and sediment transport rate increased with each run but the relative submergence remained constant for a given sediment size (Table 2) (For example, see the bold and highlighted rows in table 2). To test the effect of both relative submergence and bed slope, runs were done for in which the discharge was held constant and the bed slope increased, causing the flow depth and relative submergence to decrease, and the shear stress, and, therefore, the sediment transport rate to increase.

2.2. Sediment transport rate estimation

The collected sediment samples were dried and weighed after each run and the sediment transport rate [kg/m/s] during each run was estimated (Shvidchenko & Pender, 2000) according to:

$$q = \frac{G}{b * T} \quad (1)$$

where G is the collected and dried mass of sediment [kg], T is the sampling time [s], and b is width of the flume [0.5 m]. The bed-load transport intensity I [s^{-1}] rate, defined as the relative number of transported particles in a time unit, was estimated as follows:

$$I = \frac{m}{NT} \quad (2)$$

where m is the number of particles transported [-] during a time interval T [s] over an area of A [m^2], and N is the number of surface particles in this area [-]. Thus, the intensity is defined as the fraction of all particles transported every second. The number of particles in a bed-load sample was estimated by dividing the total dried mass of the sample by the mass of one particle. The value of N, which is the number of surface particles in the area, was estimated by assuming a surface layer with a thickness equal to one grain diameter, d:

$$N = \frac{Ad(1-\alpha)}{\frac{\Pi d^3}{6}} \quad (3)$$

where α is bed material porosity [-] and d for uniform bed sediment is equal to the mean grain size [m] and for graded sediments is equal to d_{50} [m]. The transport intensity can be also interpreted as the probability that a particle in a bed area with length L and unit width is transported every second. The area of the movable bed was estimated as follows:

$$A = b * l \quad (4)$$

where l is the effective length of the movable bed [m], which was determined using different colored sediment set at a downstream interval of 1 m along the flume (Fig. 1). The length of transport was estimated by the presence of these colors within the bed-load samples. The Einstein bed load parameter was calculated as (Shvidchenko & Pender, 2000):

$$q* = \frac{q}{f_i \rho_s \sqrt{(s-1)gd^{\ 3}}} \quad (5)$$

where s is specific gravity of sediment [-], ρ_s is sediment density [kg/m], g is gravitational acceleration [m/s], d for uniform bed sediment is equal to the mean grain size [m] and for graded sediments is equal to d_{50} [m], and f_i for uniform bed sediment [-] is equal to 1 and for graded sediment is equal to the proportion of size fraction i in the bed surface [-]. For graded beds q^* is equal to the fractional sediment transport rate. The Shields stress, τ^* [-], was estimated as:

$$\tau^* = \frac{\tau}{g(\rho_s - \rho)} = \frac{R_b S}{(s-1)d} \tag{6}$$

where $\tau = \rho g R_b S$ is the mean bed shear stress [N/m], ρ is fluid density [kg/m^3], R_b is the hydraulic radius of the bed [m], and S is bed slope [-].

In graded mixtures, there is a relative hindering and promotion effect on the transport of fine and coarse fractions, respectively, that has a significant impact on the sediment transport rate of these sediment particles (Einstein, 1950; Parker & Klingman, 1982; Wu, 2004). To examine this effect, fractional bed-load mobility was estimated as follows (Parker & Klingman, 1982):

$$\Psi i = \frac{Pi}{Fi} \tag{7}$$

where Pi [-] and Fi [-] are the fractional proportions by weight in the collected bed-load sample and within the bed sediment in the flume, respectively. The mobility can be less than 1 (reduced mobility), equal to 1 (equal mobility), or higher than 1 (enhanced mobility). Reduced/enhanced mobility takes place whenever the mobility of a fraction is lower/higher than what is anticipated for its uniform-sized counterpart, due to hiding/protrusion effects.

The critical shear stress for incipient motion in the equilibrium condition has previously been used for assessing the role of exposure and hiding on bed-load transport rates (e.g., Wilcock & Kenworthy, 2002). However, as it proves challenging to assess precisely the critical shear stress, the effect of hindering and promotion in graded sediment can also be tested using the fractional sediment transport rate. Here F_{mn} [-] is calculated, representing the impact of a fraction with diameter m [m] on sediment transport of fraction n [-] in graded sediment in comparison to its counterpart in uniform-sized sediment. The F_{mn} impact factor can be estimated as proposed by Li et al. (2016):

$$F_{mn} = \left(\frac{q_n}{f_n}\right) / \left(\frac{q_{n-uni}}{f_{n-uni}}\right) \tag{8}$$

where q_n is unit-width volumetric transport rate [kg/m] for fraction n, *uni* is for uniform-sized sediment, f_n is volumetric proportion of fraction n in the bed surface [-], and, thus, $f_{n\text{-}uni}$ for uniform-sized bed sediment is equal to 1. If the finer fractions impact on the mobility of the coarser fractions, the impact factor is greater than 1. On the contrary, if the coarser fractions impact the finer fractions, the impact factor is less than 1.

3. Results and discussion

3.1. Effect of bed slope and relative submergence on the sediment transport rate

For tests at the same relative submergence, the sediment transport rate of the uniform-sized sediment increased with bed slope (Fig. 2a-d). For example, for bed material of 5.17 mm at RS = 13.9, an increase in bed slope from 0.0075 to 0.015 resulted in a 98% increase in the transport rate. This increase is associated with an increase in discharge, and, therefore, shear stress. The effect of bed slope on the Einstein bed load parameter for a constant flow depth of 9 cm is compared between the different uniform-sized and graded sediment in Fig. 2e. The figure shows that for a given bed sediment, the bed-load parameter increased with an increase in bed slope, more so for the graded fractions, except for the coarsest fraction of 20.7 mm.

Fig. 2.

A comparison between the effect of bed slope on the bed-load parameter of graded fractions of 5.17, 10.35, 14, and 20.7 mm and their uniform-sized sediment counterpart is shown in Fig. 3. The finer fractions were more stable than the counterpart uniform-sized sediment. For example, at a bed slope of 0.015 m/m and a flow depth of 10 cm, the bed-load parameter of uniform bed sediment of 5.17 and 10.35 mm was 380 and 310 times higher than that of the counterpart graded fractions (Fig. 3a, b). However for sediment of a size of 14 mm, the bed-load parameter was almost equal for the uniform-sized and graded sediment (Fig. 3c). Also, at a grain size of 20.7 mm the bed-load parameter of the graded fraction was 5.2 times greater than its uniform-sized counterpart at a bed slope of 0.03 m/m and a flow depth of 10 cm (Fig. 3d). This difference in mobility of the finer and coarser fractions between the uniform-sized and graded sediment can be attributed to the greater hiding and protrusion that occurs in the later (Li et al., 2016; Wang et al., 2015). Despite this difference, the transport rate of the graded fractions and their uniform-sized material counterpart increased at a similar rate with bed slope.

Fig. 3.

Figure 4 shows an example of the change in the sediment transport rate with bed slope and relative submergence for the tests done at the same flow discharge. In these tests an increase in bed slope corresponded to a decrease in relative submergence. The figure shows that the bed-load transport rate increased with bed slope and decreased with relative submergence. For example, for bed material of 5.17 mm, an increase in bed slope from 0.005 to 0.015 mm^{-1}, corresponding with a decrease in *RS* from 17.4 to 11.6, and caused a 99% increase in the transport rate. This result occurred because the shear stress was higher at the steeper slopes and lower submergences. A comparison between the graded fractions and their uniform counterparts (Fig. 4c) shows that the finer fractions than d_{50} (e.g., 5.17 and 10.35 mm) had a lower transport rate, the 14 mm fraction had an equal transport rate and the coarsest fraction of 20.7 mm had a higher transport rate, than their uniform-sized counterparts.

Fig. 4.

The transport rate increased with relative submergence because higher submergences were related to higher shear stress (Fig. 5). For example, for uniform sizes of 5.17, 10.35, 14, 20.7 mm, and the graded sediment, a 1.6, 1.3, 1.3, 1.5, and 1.2 times increase in *RS* at a constant bed slope of 0.01 m/m, caused 15, 41, 52, 5 and 16 times increases in transport rate, respectively.

Fig.5.

3.2. Effect of relative submergence on the Einstein bed-load parameter and inter-granular effects

Figure 6a shows the relation between the Einstein bed-load parameter and relative submergence at a fixed bed slope of 0.015 m/m for uniform bed materials of 5.17, 10.35, 14 mm, and the graded sediment. There was a clear increase in the bed-load parameter with relative submergence, and the rate of increase was fairly invariant with sediment size. In contrast, relative submergence had a much greater impact on the sediment transport rate of the coarser fractions within the graded mixture (Fig. 6b).

Fig. 6.

Figure 7 shows the degree to which the impact factor (IF) changed with relative submergence. For example, F_{20} represents the impact of three fractions (5.17, 10.35, and 14 mm) on the sediment transport behavior of fraction 20.7 mm. Results show that for F_{20} and F_{14}, *IF* was higher than 1 meaning finer fractions caused an increase in the transport rate of fractions of 20.7 and 14 mm in comparison to their uniform-sized counterparts. For F_{10}, the *IF* values at both slopes of 0.015 and 0.03 m/m were lower than 1 indicating that the other fractions (5.17, 14, and 20.7 mm) caused a relative decrease in the sediment transport rate of fraction of 10 mm in comparison to the uniform counterpart. These observations show that fine fractions enhanced the sediment transport rate of the coarser fractions and the total sediment transport rate, and that coarser fractions reduced the transport rate of finer fractions. This result is in accordance with results for equilibrium (e.g., Venditti et al., 2010; Wilcock & Crowe, 2003; Wilcock et al., 2001;

Wilcock & McArdell, 1997) and degrading conditions (Li et al., 2016). This behavior occurred because finer fractions tended to hide between or behind coarser fractions, whilst the coarser fractions were more exposed to the higher hydrodynamic forces further up in the flow (Einstein, 1950). Fig. 7 also reveals that the *IF* values for the coarser fraction deceased with a rise in relative submergence and that the opposite trend occurred for the finer fractions. In other words, as relative submergence increased the graded fractions tended towards behaving more like their uniform-sized counterparts. This change is likely to have occurred because at high relative submergences there was a larger shear stress, and, thus, the hydrodynamic exposure of the different fractions differed less than at lower submergences, acting to reduce the promotion-hindering effect on transport rates.

Fig. 7.

3.3. Effect of Shields stress on the bed-load parameter

A comparison between the effect of Shields stress on the bed-load parameter for the graded fractions and their uniform-sized counterparts is shown in Fig. 8. In the case of 10.35 mm, the Shields stress and the Einstein bed load parameter for uniform sediment was higher than the graded fraction (Fig. 8a). But for sizes of 14 and 20.7 mm, these parameters were lower (Fig. 8b, c). This hindering and promotion effect is in accordance with the results of Li et al. (2016) for mixtures of sand and gravel, and attributed to the elevated hiding and protrusion of fine and coarse fractions within a graded mixture.

Fig.8.

3.4. Effect of bed slope on fractional bed load mobility

Generally the mobility of the coarser fractions, (coarser than d_{50}), was higher than 1 but the mobility of finer fractions (finer than d_{50}) was lower than 1 (Fig. 9), as one might expect from the results in Fig. 8. The highest relative mobility belongs to the 20.7 mm fraction, followed by 14, 10.35, and 5.17 mm. These differences are reflected in the bed-load grain size distribution; in all experimental runs the transported sediment of the graded mixture was coarser than the bed surface composition. An example is shown in Fig. 10 for the run done at a bed slope of 0.03 m/m and RS = 6.4.

The results in Fig. 8 also reveal that an increase in bed slope caused the mobility of the coarser fractions to increase from 1 at a slope of 0.015 m/m to 1.8 at a slope of 0.03 m/m, but the finest fraction reduced from 0.3 to 0.13 (Fig. 9). This change with bed slope occurred because at higher slopes there is a larger shear stress, and, thus, greater hydrodynamic exposure of the coarser grains than would occur at lower slopes, making their relative mobility higher at steeper slopes. Thus, the finer fractions at higher slopes became relatively less exposed than would occur at lower slopes, in comparison to the coarser fractions.

Fig 9.

Fig 10.

3.5. Implications and recommendations

The results have a number of implications. First, under degrading channel conditions, such as downstream of a dam, coarser grain-size fractions in a poorly-sorted sediment, relative to uniform-sized sediment, reduce the transport of finer grains and finer fractions enhance the transport of coarse grains. This result confirms that bed-load equations developed for uniform bed sediment are inappropriate for use in natural river systems. Second, this hindering-promotion effect, caused by relative hiding and exposure of finer and coarse fractions, increased with bed slope and decreased with relative submergence. Thus, the errors in the use of these equations are likely to be most critical in mountain streams. Third, the large difference in the transport rates of the fine and coarse fractions of the poorly-sorted sediment in comparison to their uniform-sized counterparts also indicates that changes in bed composition could lead to significant changes in river morphology. Such changes could be caused by natural or human activities, such as fire, logging, flow diversion, road construction, and agricultural development. Thus, measures that control the input of catchment-stored sediment that differ to those of river bed sediment, such as soil conservation techniques, grass-planting, afforestation, buffer strips, and check-dams, will play a useful role in reducing river morphological change.

Future studies should consider a wider range of poorly-sorted sediment than studied here, and a wider range of non-equilibrium conditions, such as in the case of an upstream sediment supply. Also, information on the changes in bed surface composition and topography, and in the near-bed flow field, would further elucidate the impact of bed slope and relative submergence on the effect of hiding and exposure on the mobility of poorly-sorted sediment.

4. Conclusions

Laboratory experiments in a recirculating flume have quantified the effect of bed grain size variation on bed-load transport. A comparison between of the sediment transport behavior of fractions in a graded mixture with their counterpart uniform-sized sediment revealed that finer fractions had a lower Shields stress and Einstein bed load parameter. In contrast, the coarser fractions had a higher Shields stress and Einstein bed load parameter. This difference in mobility was attributed to hiding and protrusion effects, and was most pronounced at higher slopes and lower relative submergences. In particular, as relative submergence increased the graded fractions tended towards behaving more like their uniform-sized counterparts. Also, the bed-load parameter of the graded fractions increased more with an increase in bed slope than observed for the uniform sized counterparts. These results reveal, under degrading channel conditions, such as downstream of a dam, bed-load equations developed for uniform bed sediment are inappropriate for use in natural river systems, particularly in mountain streams. The large difference in the transport rates of the fine and coarse fractions of the poorly-sorted sediment in comparison to their uniform-sized counterparts also indicates that changes in bed composition could lead to significant changes in river morphology. Thus, measures that control the input of hill-slope erosion, due to activities such as fire, logging, and agricultural development, could play an important role in reducing river morphological change.

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Figure captions

Fig. 1. Experimental flume set-up (not to scale).

Fig. 2. Effect of bed slope on sediment transport rate at a constant flow depth for uniform-sized bed sediment of (a) 5.17 mm, (b) 10.35 mm, (c), 14 mm and (d), 20.7 mm for uniform-sized and (e) graded sediment.

Fig. 3. A comparison between the effect of bed slope on the bed load parameter for uniform-sized and graded sediment.

Fig. 4. Effect of (a) bed slope and (b) relative submergence on the sediment transport rate for uniform sediment of 5.17 mm, and (c) effect of bed slope on sediment transport rate for all uniform-sized and counterpart fractions.

Fig. 5. A comparison between the effect of relative submergence on sediment transport for uniform-sized and graded sediment.

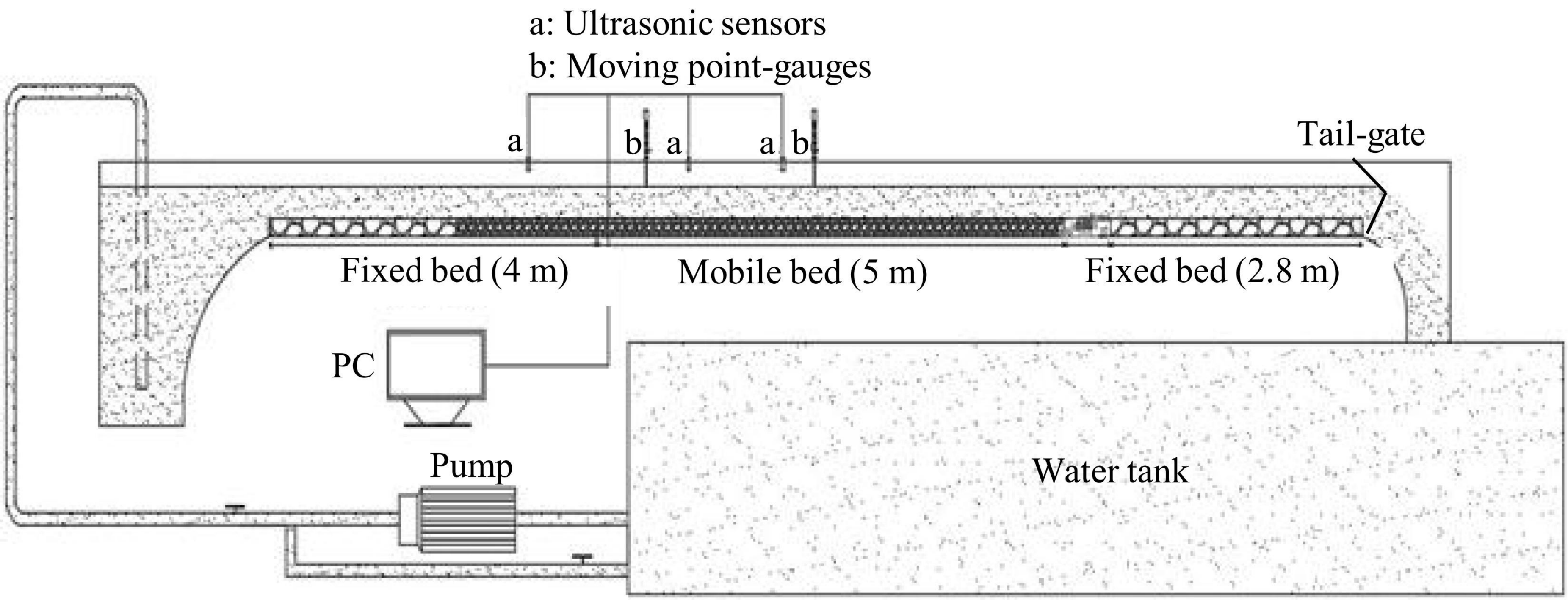
Fig. 6. Effect of relative submergence on (a) the Einstein bed load parameter for graded and uniform-sized sediment at a bed slope of 0.015 m/m and (b) total and fractional sediment transport rate of the graded mixture at a bed slope of 0.015 m/m.

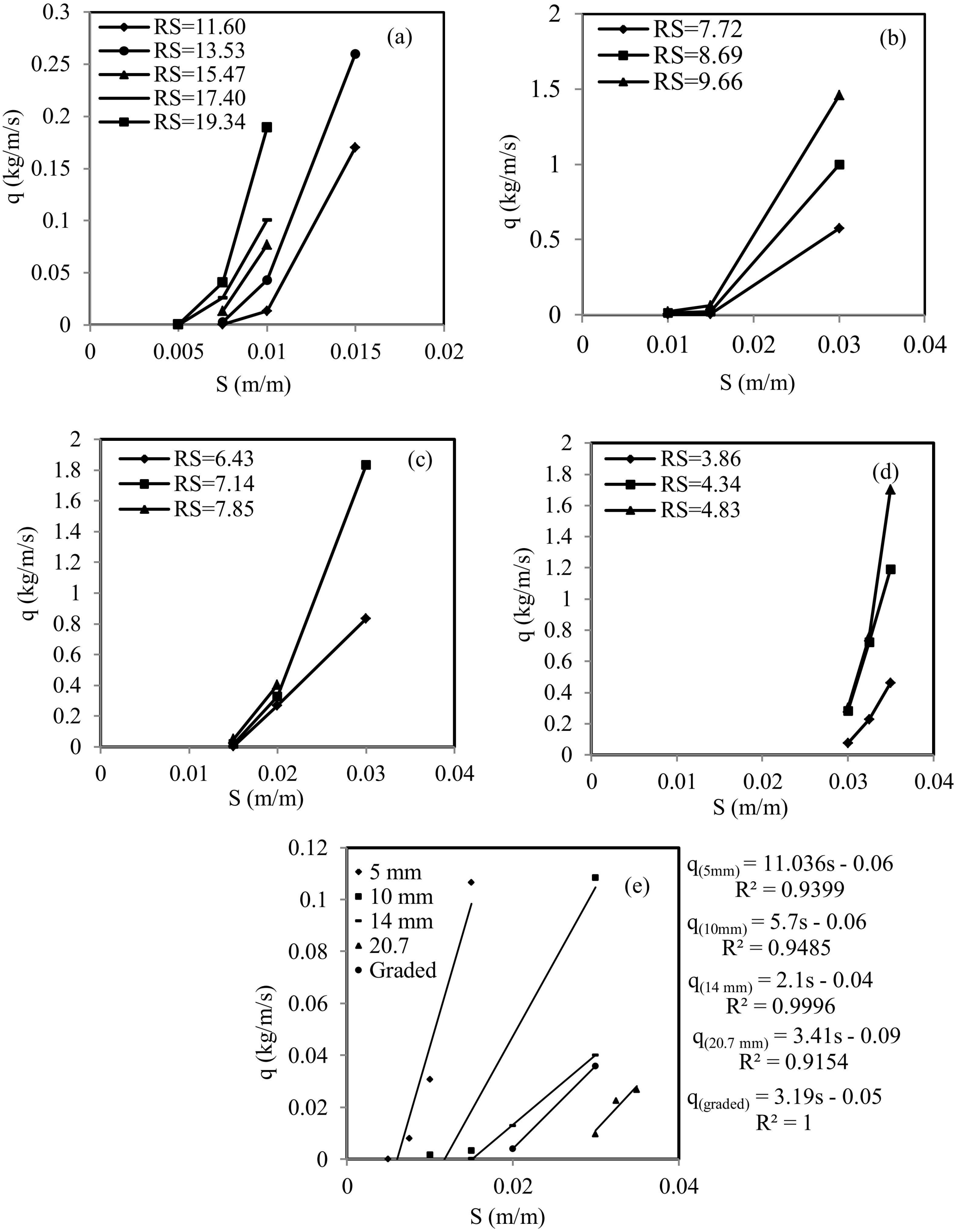
Fig. 7. Effect of relative submergence on the impact factor.

Fig. 8. Effect of Shields stress on the Einstein bed load parameter for uniform-sized and counterpart graded fractions of (a) 10.35 mm, (b), 14 mm, and (c) 20.7 mm.

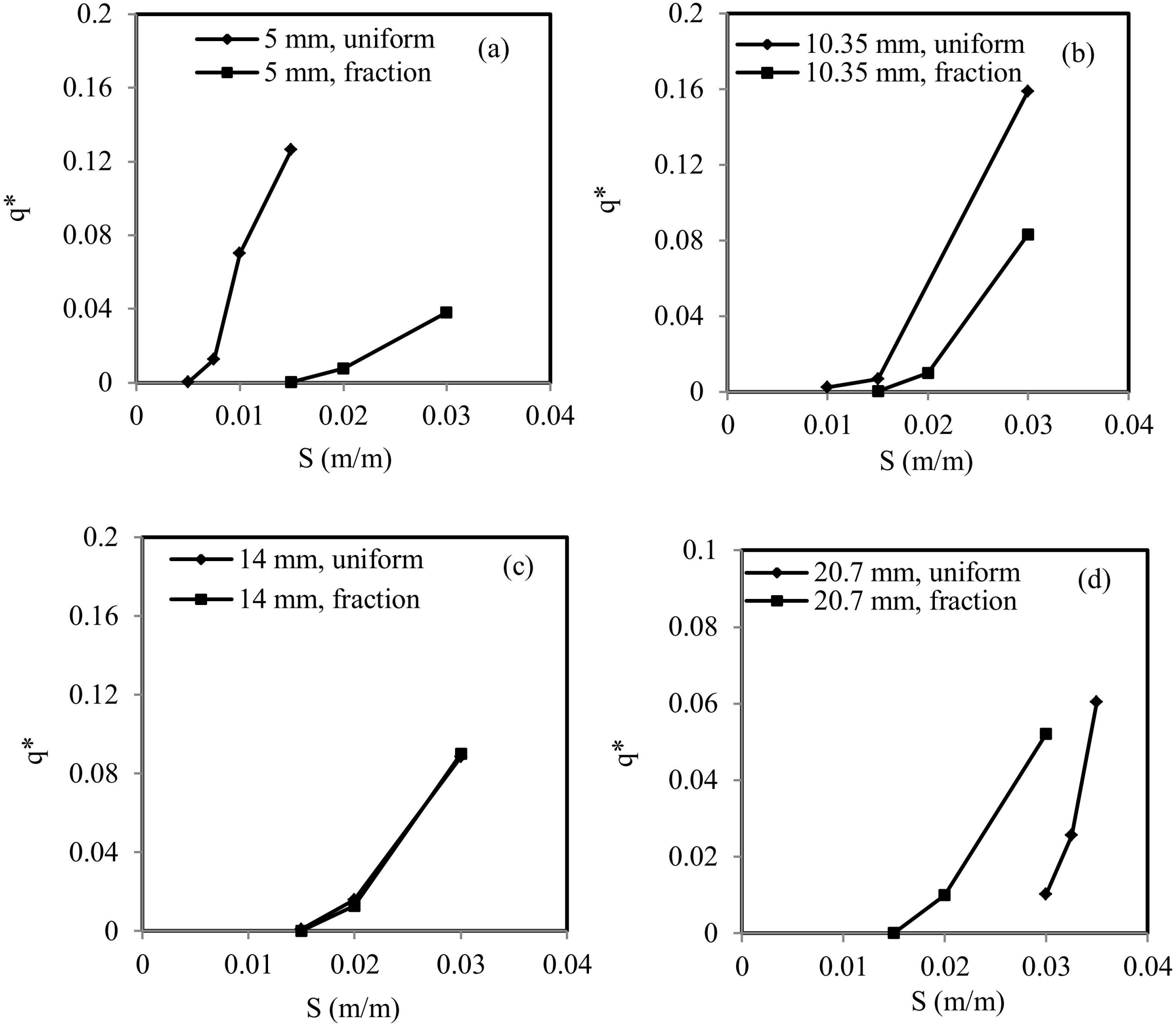
Fig. 9. Effect of bed slope on fractional bed load mobility.

Fig. 10. Size distribution of transported sediment and the bed surface at a bed slope of 0.03 m/m and a relative submergence of 6.4.

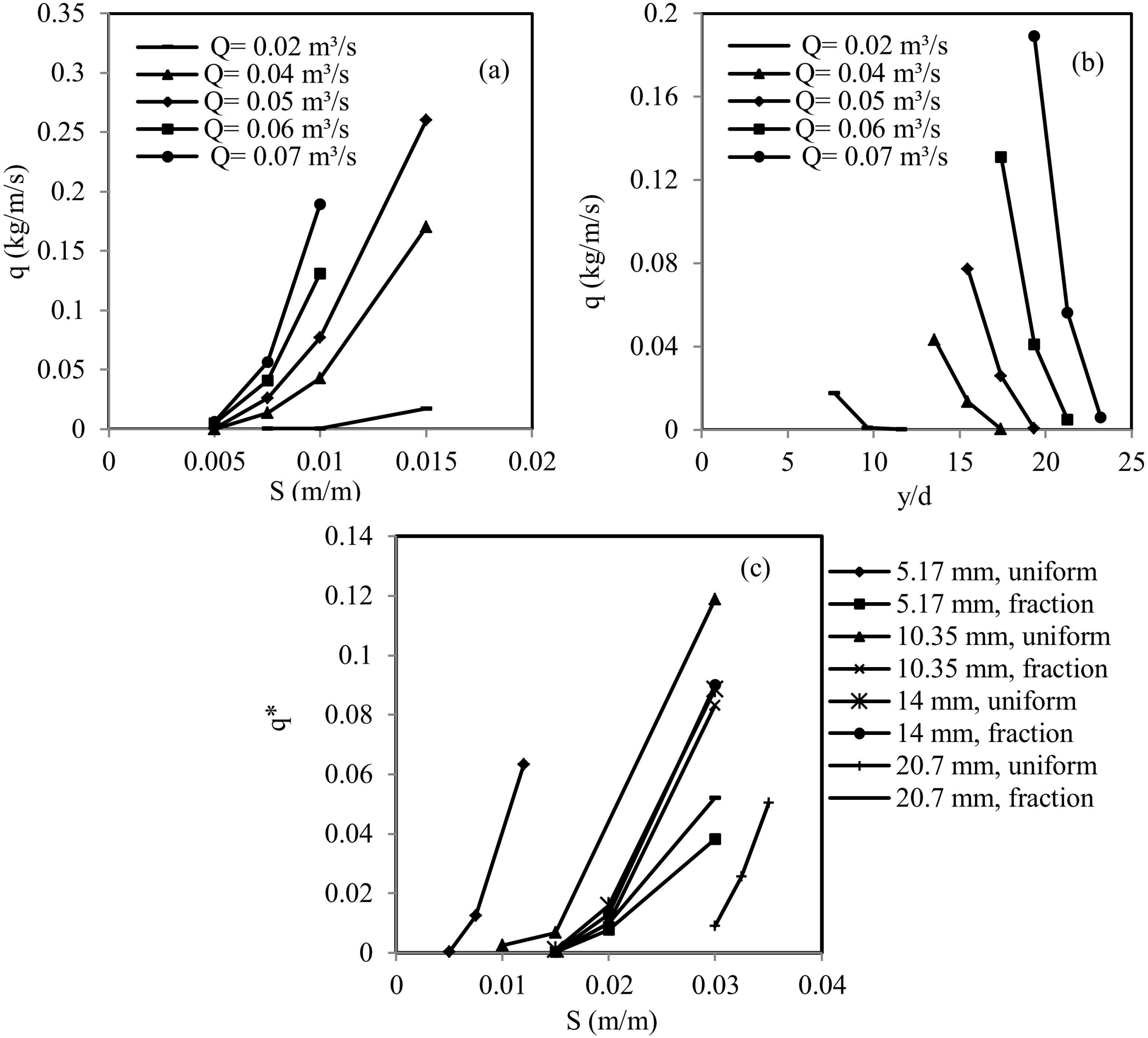

a: Ultrasonic sensors
b: Moving point-gauges
a
b
a
a
b
Tail-gate
Fixed bed (4 m)
Mobile bed (5 m)
Fixed bed (2.8 m)
PC
Pump
Water tank

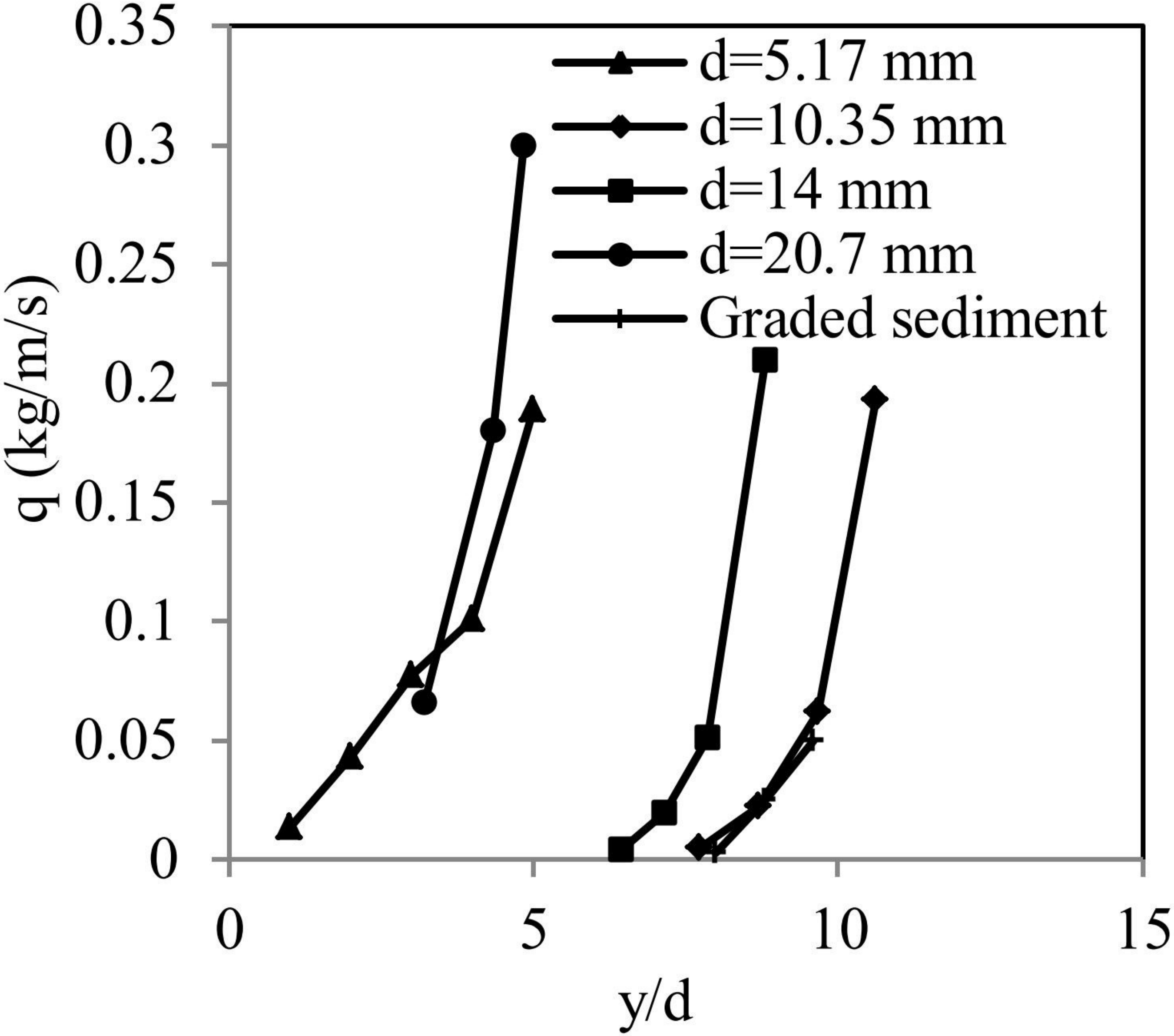


(a)
RS=11.60
RS=13.53
RS=15.47
RS=17.40
RS=19.34
q (kg/m/s)
S (m/m)
(b)
RS=7.72
RS=8.69
RS=9.66
q (kg/m/s)
S (m/m)
(c)
RS=6.43
RS=7.14
RS=7.85
q (kg/m/s)
S (m/m)
(d)
RS=3.86
RS=4.34
RS=4.83
q (kg/m/s)
S (m/m)
(e)
5 mm
10 mm
14 mm
20.7
Graded
q (kg/m/s)
S (m/m)
$q_{(5mm)} = 11.036s - 0.06$
$R^2 = 0.9399$
$q_{(10mm)} = 5.7s - 0.06$
$R^2 = 0.9485$
$q_{(14\ mm)} = 2.1s - 0.04$
$R^2 = 0.9996$
$q_{(20.7\ mm)} = 3.41s - 0.09$
$R^2 = 0.9154$
$q_{(graded)} = 3.19s - 0.05$
$R^2 = 1$

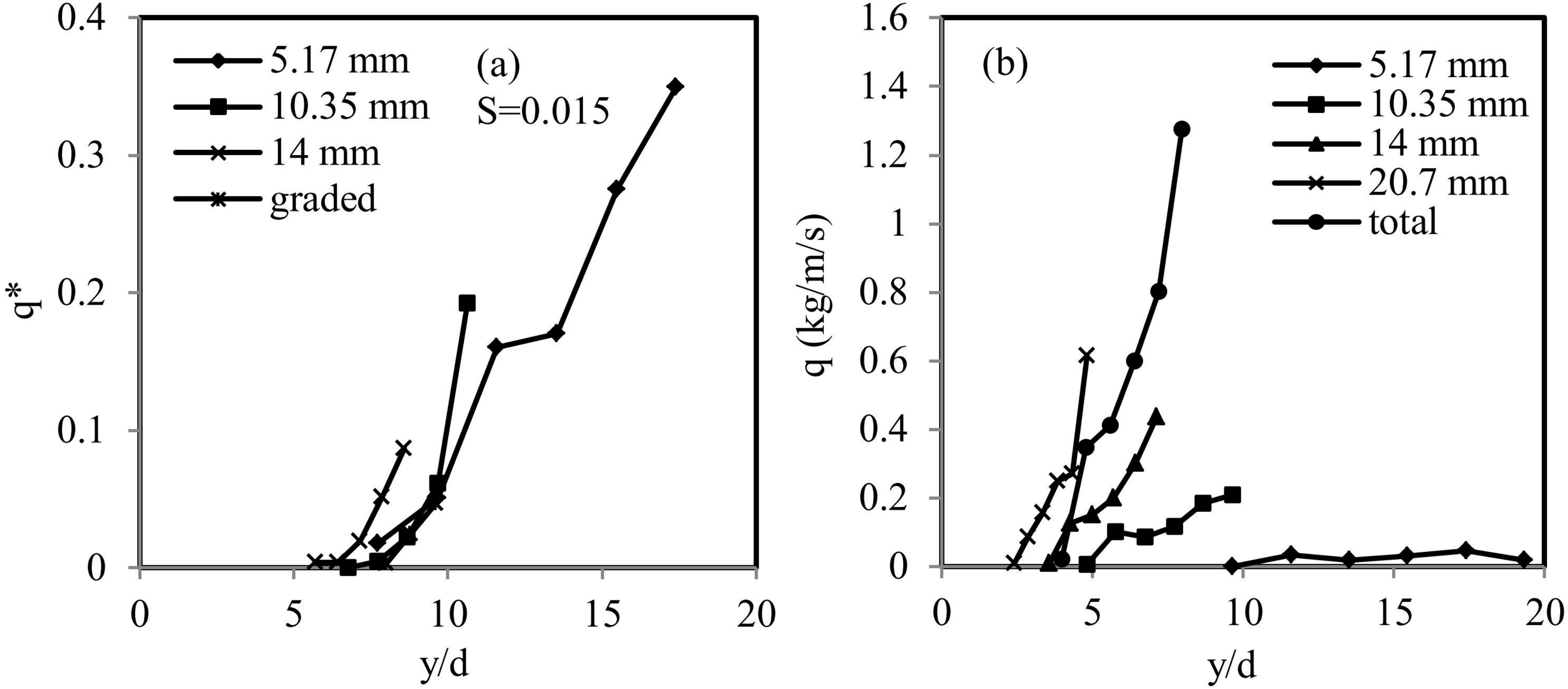


(a)
5 mm, uniform
5 mm, fraction
q*
S (m/m)
(b)
10.35 mm, uniform
10.35 mm, fraction
q*
S (m/m)
(c)
14 mm, uniform
14 mm, fraction
q*
S (m/m)
(d)
20.7 mm, uniform
20.7 mm, fraction
q*
S (m/m)

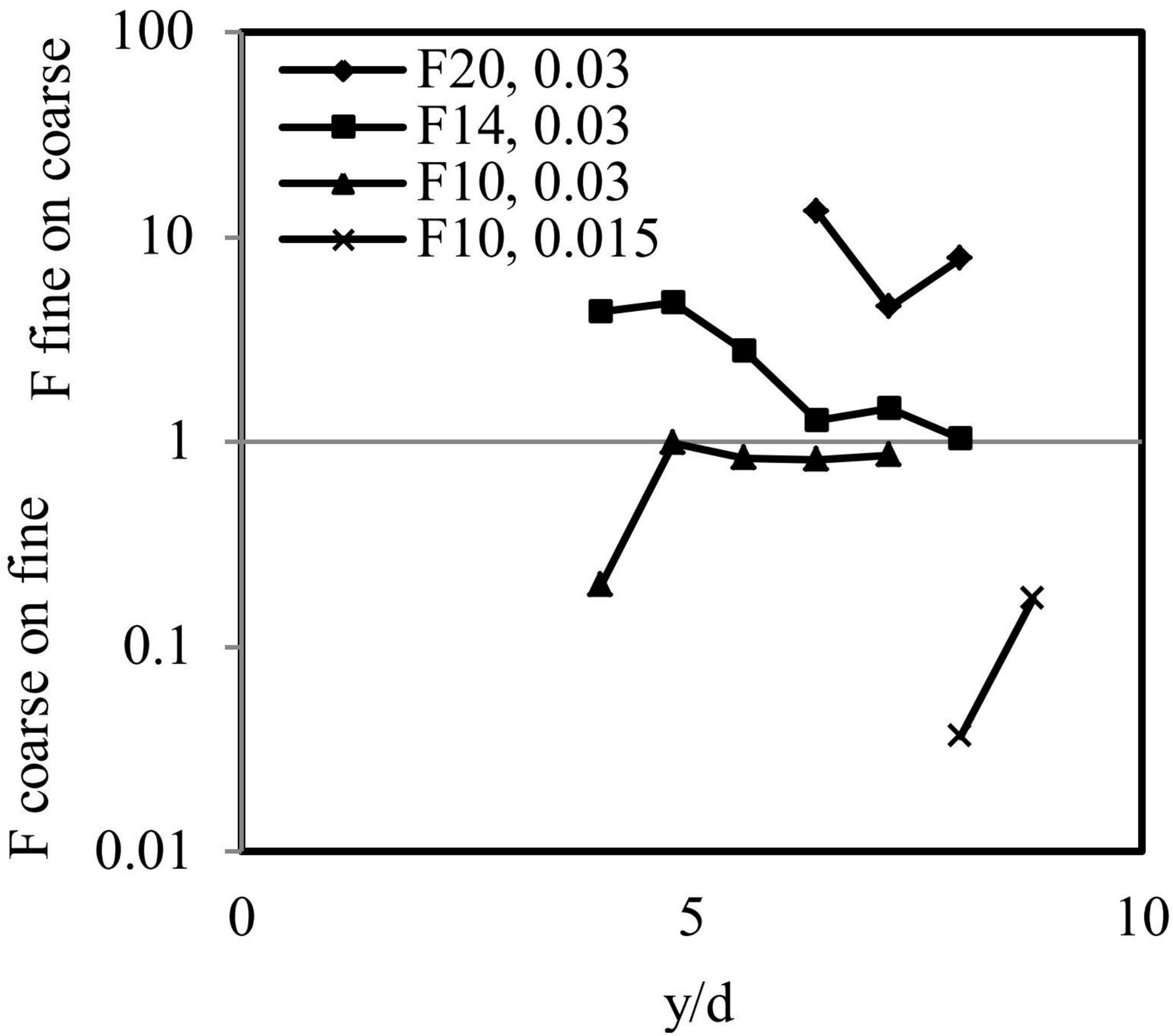

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
q (kg/m/s)
Q= 0.02 m³/s
Q= 0.04 m³/s
Q= 0.05 m³/s
Q= 0.06 m³/s
Q= 0.07 m³/s
(a)
0
0.005
0.01
0.015
0.02
S (m/m)
0.2
0.16
0.12
0.08
0.04
0
q (kg/m/s)
Q= 0.02 m³/s
Q= 0.04 m³/s
Q= 0.05 m³/s
Q= 0.06 m³/s
Q= 0.07 m³/s
(b)
0
5
10
15
20
25
y/d
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
q*
(c)
5.17 mm, uniform
5.17 mm, fraction
10.35 mm, uniform
10.35 mm, fraction
14 mm, uniform
14 mm, fraction
20.7 mm, uniform
20.7 mm, fraction
0
0.01
0.02
0.03
0.04
S (m/m)



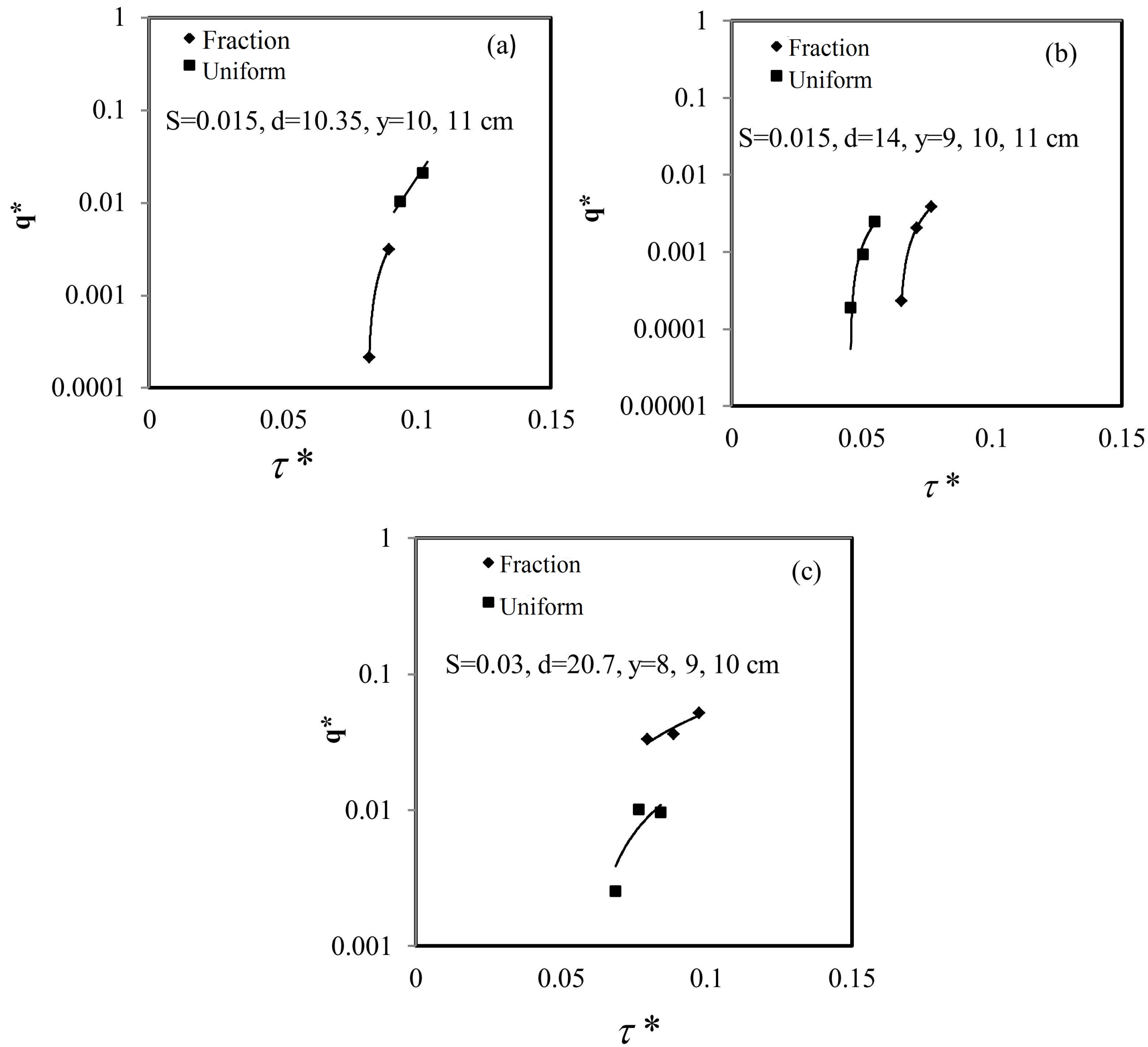
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
q (kg/m/s)
0
5
10
15
y/d
d=5.17 mm
d=10.35 mm
d=14 mm
d=20.7 mm
Graded sediment

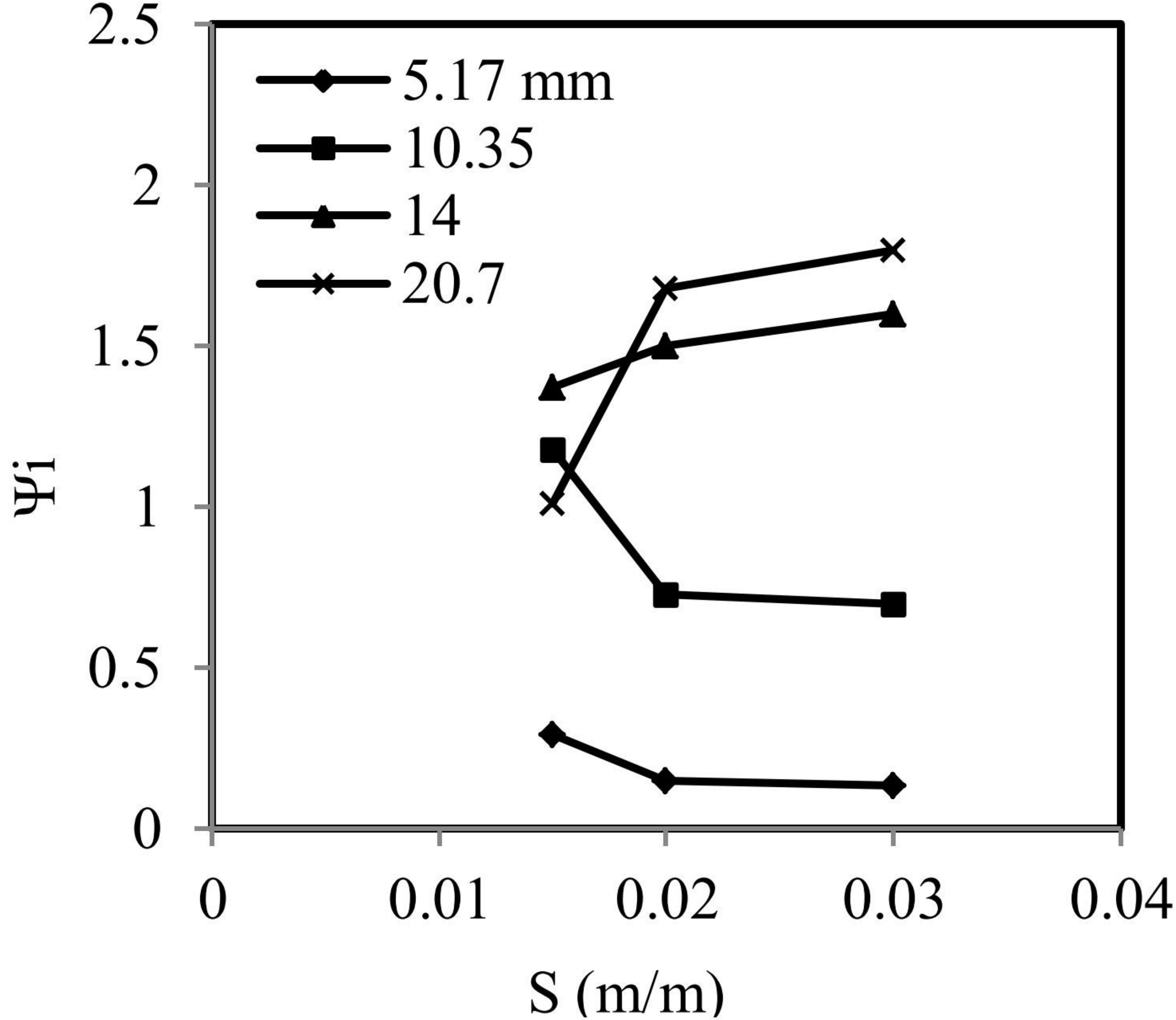


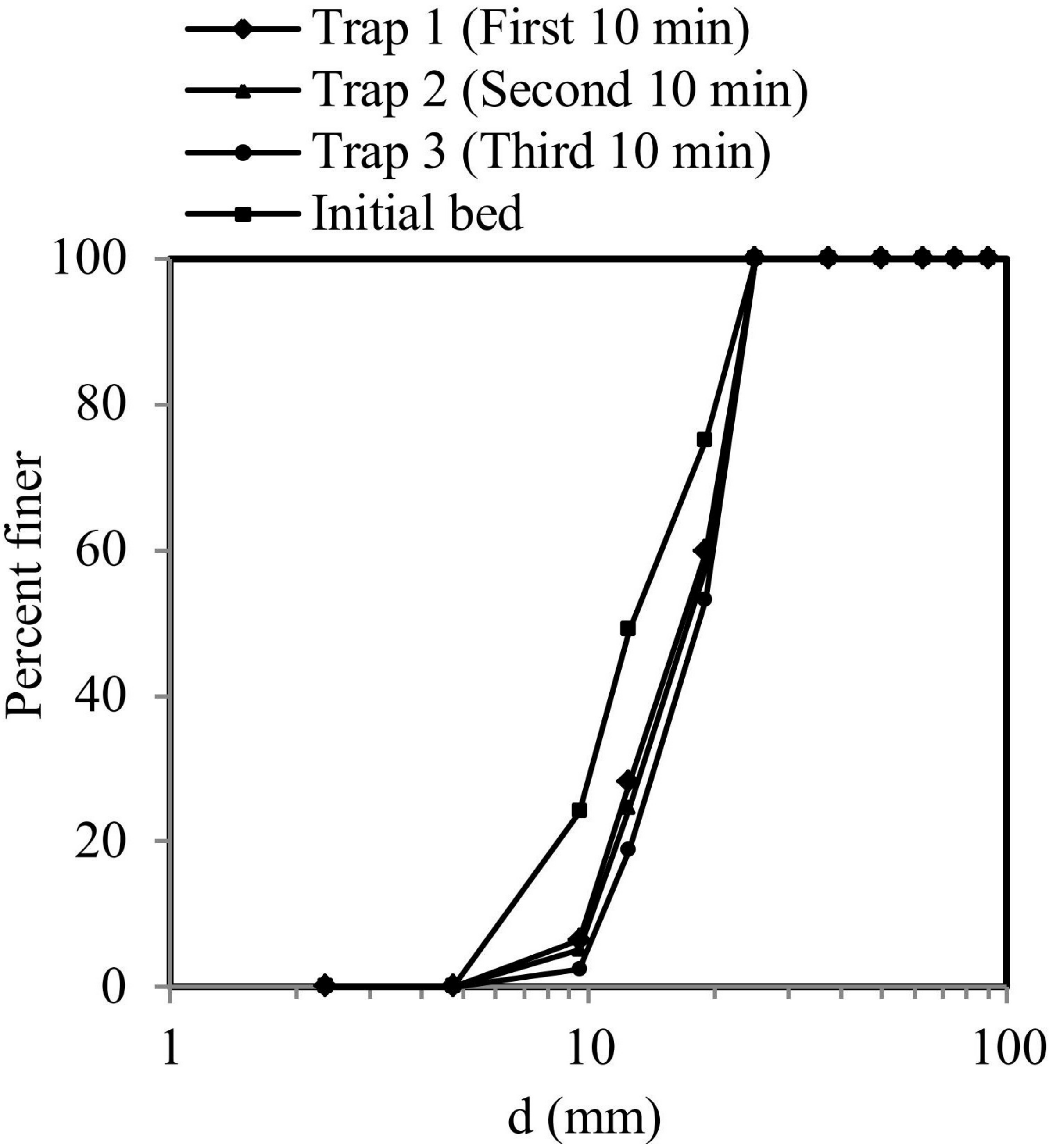
0.4
0.3
0.2
0.1
0
q*
0
5
10
15
20
y/d
5.17 mm
10.35 mm
14 mm
graded
(a)
S=0.015
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
q (kg/m/s)
(b)
5.17 mm
10.35 mm
14 mm
20.7 mm
total



F fine on coarse
F coarse on fine
100
10
1
0.1
0.01
0
5
10
y/d
F20, 0.03
F14, 0.03
F10, 0.03
F10, 0.015


(a)
Fraction
Uniform
S=0.015, d=10.35, y=10, 11 cm
q*
τ *
1
0.1
0.01
0.001
0.0001
0
0.05
0.1
0.15
(b)
Fraction
Uniform
S=0.015, d=14, y=9, 10, 11 cm
q*
τ *
1
0.1
0.01
0.001
0.0001
0.00001
0
0.05
0.1
0.15
(c)
Fraction
Uniform
S=0.03, d=20.7, y=8, 9, 10 cm
q*
τ *
1
0.1
0.01
0.001
0
0.05
0.1
0.15


5.17 mm
10.35
14
20.7
2.5
2
1.5
1
0.5
0
Ψi
0
0.01
0.02
0.03
0.04
S (m/m)



Trap 1 (First 10 min)
Trap 2 (Second 10 min)
Trap 3 (Third 10 min)
Initial bed
Percent finer
d (mm)
0
20
40
60
80
100
1
10
100

Table 1. Bed sediment properties

Sediment	Fractions (mm)	Mean size, d (mm)	Median size, d_{50} (mm)	σ_g [-]	Density, (kg/m^3)	Porosity [-]	Grain shape [-]
Fine gravel	4.8-5.5	5.17	-	-	2,391	0.4	Rounded
Medium gravel 1	9.5-11	10.35	-	-	2,375	0.4	Rounded
Medium gravel 2	13-15	14	-	-	2,900	0.45	Rounded
Coarse gravel	19-22.4	20.7	-	-	2,552	0.43	Rounded
Graded (mixture)	4.8-22.4	13.5	12.5	1.7	2,567	0.37	Rounded

Table 2. Summary of the experimental conditions

ID	*d* (mm)	Slope, *S* (m/m)	*y* (cm)	Mean velocity, *V* (m/s)	Relative submergence, *RS [-]*	*Fr* [-]	*Re [-]*	τ^* *[-]*	*V* [-]*
1	5.17	0.005	**9**	**0.92**	**17.4**	**0.97**	**60,882**	**0.055**	**0.062**
2			10	1	19.3	1	71,428	0.060	0.065
3			11	1.1	21.2	1.05	84,027	0.065	0.068
4			12	1.2	23.2	1.1	97,297	0.070	0.071
5		0.0075	6	0.83	11.6	1.08	40,161	0.057	0.064
6			7	0.96	13.5	1.15	52,500	0.066	0.068
7			8	1.1	15.4	1.24	66,666	0.074	0.073
8			**9**	**1.2**	**17.4**	**1.27**	**79,411**	**0.082**	**0.076**
9			10	1.27	19.3	1.28	90,714	0.090	0.080
10			11	1.33	21.2	1.29	101,597	0.098	0.083
11			12	1.4	23.2	1.3	113,513	0.106	0.087
12		0.01	4	0.75	7.0	1.19	25,862	0.052	0.061
13			5	0.94	9.6	1.24	39,166	0.065	0.067
14			6	1.08	11.6	1.31	52,258	0.076	0.073
15			7	1.13	13.5	1.37	61,796	0.088	0.079
16			8	1.25	15.4	1.44	75,757	0.099	0.084
17			**9**	**1.3**	**17.4**	**1.38**	**86,029**	**0.110**	**0.088**
18			10	1.35	19.3	1.36	96,428	0.121	0.092
19		0.015	4	1	7.0	1.58	34,482	0.078	0.074
20			5	1.11	9.6	1.59	46,296	0.096	0.083
21			6	1.25	11.6	1.61	60,483	0.114	0.090
22			7	1.3	13.5	1.58	71,093	0.130	0.097
23			8	1.4	15.4	1.59	84,848	0.149	0.103
24			**9**	**1.5**	**17.4**	**1.6**	**99,264**	**0.165**	**0.108**
25	10.35	0.01	8	1.11	7.7	1.25	67,340	0.051	0.084
26			9	1.2	8.6	1.27	79,411	0.056	0.089
27			10	1.3	9.6	1.3	92,857	0.062	0.093
28			11	1.42	10.6	1.36	108,472	0.067	0.097
29		0.015	7	1.1	6.7	1.32	60,156	0.067	0.097
30			8	1.2	7.7	1.35	72,727	0.076	0.103
31			9	1.31	8.6	1.39	86,691	0.085	0.109
32			10	1.42	9.6	1.43	101,428	0.093	0.114
33			11	1.52	10.6	1.46	116,111	0.101	0.119
34		0.03	4	1.05	3.8	1.67	36,206	0.080	0.106
35			5	1.25	4.8	1.78	52,083	0.098	0.118
36			6	1.5	5.7	1.95	72,580	0.117	0.128
37			7	1.62	6.7	1.96	88,867	0.135	0.138
38			8	1.75	7.7	1.97	106,060	0.153	0.146
39			9	1.85	8.6	1.96	122,426	0.170	0.154
40			10	2	9.6	2.00	142,857	0.187	0.162
41	14	0.015	8.5	1.3	6.0	1.42	82,462	0.044	0.107
42			9	1.4	6.4	1.48	92,647	0.045	0.109
43			10	1.5	7.1	1.40	74,230	0.050	0.115
44			11	1.65	7.8	1.58	126,041	0.055	0.120
45			12	1.75	8.5	1.61	141,891	0.059	0.125
46		0.02	6.5	1.19	4.6	1.49	61,388	0.045	0.109
47			7	1.3	5	1.56	71,093	0.048	0.113
48			8	1.4	5.7	1.58	84,848	0.054	0.120
49			9	1.6	6.4	1.7	105,882	0.061	0.126
50			10	1.8	7.1	1.81	128,571	0.067	0.133

51			11	2	7.8	1.92	152,777	0.073	0.138
52		0.03	4.5	1.1	3.2	1.63	42,736	0.049	0.113
53			5	1.3	3.5	1.85	54,166	0.053	0.118
54			6	1.55	4.2	2.00	75,000	0.063	0.128
55			7	1.67	5	2.00	91,328	0.072	0.138
56			8	1.75	5.7	1.97	106,060	0.082	0.148
57			9	1.9	6.4	2.02	125,735	0.091	0.155
58			10	2.1	7.1	2.12	150,000	0.101	0.162
59			11	2.4	7.8	2.25	157,145	0.108	0.165
60	20.7	0.03	8	1.66	3.8	1.87	100,606	0.068	0.147
61			9	2.08	4.3	2.21	137,647	0.076	0.155
62			10	2.17	4.8	2.19	155,000	0.084	0.163
63		0.0325	6	1.42	2.9	1.85	68,709	0.056	0.134
64			7	1.61	3.3	1.92	88,046	0.065	0.144
65			8	1.76	3.8	1.99	106,666	0.074	0.153
66			9	1.92	4.3	2.06	127,058	0.083	0.162
67			10	2.2	4.8	2.22	157,142	0.091	0.170
68		0.035	5	1.35	2.4	1.92	56,250	0.051	0.128
69			6	1.5	2.9	1.95	72,580	0.061	0.139
70			8	1.8	3.8	2.03	109,090	0.080	0.159
71			9	2	4.3	2.12	132,353	0.089	0.168
72			10	2.3	4.8	2.32	164,285	0.098	0.176
73	Graded	0.015	10	1.51	8	1.52	107,857	0.068	0.115
74			11	1.65	8.8	1.58	126,041	0.075	0.120
75			12	1.8	9.6	1.65	145,945	0.080	0.124
76		0.02	7	1.25	5.6	1.50	68,359	0.065	0.112
77			8	1.33	6.4	1.50	80,606	0.074	0.120
78			9	1.56	7.2	1.66	103,235	0.082	0.126
79			10	1.7	8	1.71	121,428	0.091	0.132
80			11	1.82	8.8	1.75	139,027	0.099	0.138
81		0.03	5	1.25	4.0	1.78	52,083	0.072	0.118
82			6	1.5	4.8	1.95	72,580	0.085	0.128
83			7	1.67	5.6	2.01	91,328	0.098	0.138
84			8	1.72	6.4	1.94	104,242	0.111	0.147
85			9	1.85	7.2	1.96	122,426	0.124	0.155
86			10	2	8	2.01	142,857	0.136	0.162

(Froude number (Fr), Reynolds number (Re), Shields stress (τ^*), and shear velocity (V^*)).