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Graded and uniform bed load sediment transport in a degrading channel

Zhijing Li¹, Zhixian Cao², Huaihan Liu³ and Gareth Pender⁴

Abstract: Twenty runs of experiments are carried out to investigate non-equilibrium transport of graded and uniform bed load sediment in a degrading channel. Well sorted gravel and sand are employed to compose four kinds of sediment beds with different gravel/sand contents, i.e., uniform 100% gravel bed, uniform 100% sand bed, and two graded sediment beds respectively with 53% gravel and 47% sand as well as 22% gravel and 78% sand. For different sediment beds, the experiments are conducted under the same discharges, thereby allowing for the role of sediment composition in dictating the bed load transport rate to be identified. A new observed dataset is generated concerning the flow, sediment transport and evolution of bed elevation and composition, which can be exploited to underpin developments of mathematical river models. The data shows that in a degrading channel, the sand greatly promotes the transport of gravel, whilst the gravel considerably hinders the transport of sand. The promoting and hindering effects are evaluated by means of impact factors defined based on sediment transport rates. The impact factors are shown to vary with flow discharge by orders of magnitude, being most pronounced at the lowest discharge. It is characterized that variations in sand or gravel inputs as a result of human activities and climate change may lead to severe morphological changes in degrading channels.

Key words: sediment transport; bed load; gravel; sand; promoting; hindering

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1. Introduction

Sediment transport in alluvial rivers has important consequences for public safety, management of land, water, ecological resources, and environmental sustainability (Chien & Wan, 1999; Frey & Church, 2009; Graf, 1971; Raven et al., 2010; Wilcock, 1998). Generally, sediment can be transported as bed load and suspended load, depending on sediment characteristics and flow conditions. This work focuses on bed load transport, in which sediment particles move over the stream in a sliding, rolling or saltating mode (Gomez, 1991). A number of formulas have been developed to date to describe bed load transport (Einstein, 1950; Engelund & Hansen, 1967; Meyer-Peter & Müller, 1948). However, most studies are based on uniform sediment under steady flow conditions. The prediction of sediment transport in natural rivers continues to be one of the major challenges for fluvial hydraulics and morphodynamics, which is mainly due to the presence of different types of unsteady flows and the sophisticated mutual impact between various grain size fractions in graded bed materials (Bagnold, 1977).

The last several decades have seen a number of experimental investigations of graded bed load sediment transport in open channels. The majority of the experiments were conducted in equilibrium conditions (e.g., Kuhnle, 1993a, 1993b; Kuhnle et al., 2013; Wilcock & Crowe, 2003; Wilcock & Kenworthy, 2002; Wilcock et al., 2001; Wilcock & McArdell, 1993, 1997). Most notably, promoting/hindering impacts of fine/coarse sediment on the transport of coarse/fine sediment were revealed in these experiments, as characterized by changes in the critical shear stress for incipient motion of graded sediment. These experiments along with other laboratory and field observations have led to the development of a range of formulations for graded bed load transport rate (Almedeij et al., 2006; Patel & Ranga Raju, 1996; Wilcock & Crowe, 2003; Wilcock & Kenworthy, 2002; Wu et al., 2000).

Non-equilibrium cases comprise both aggradation and degradation cases. For aggradation cases, there have been many flume experimental investigations (e.g., Cui et al., 2003a; Paola et al., 1992; Seal et al., 1997; Solari & Parker, 2000; Toro-Escobar et al., 2000; Venditti et al., 2010a, 2010b).
These experiments have produced an abundance of observed data (typically, of flow depth, sediment transport rate, bed elevation and composition) to support the development of mathematical river models (Belleudy & Sogreah, 2000; Cui, 2007; Cui et al., 1996; Cui et al., 2003b; Hu et al., 2014; Qian et al., 2015; Wu, 2004; Wu & Wang, 2008), which numerically solve the shallow water hydrodynamic equations along with continuity equations for sediment and the bed. Extending the finding of promoting and hindering impacts for equilibrium cases (Kuhnle, 1993a, 1993b; Kuhnle et al., 2013; Wilcock & Crowe, 2003; Wilcock & Kenworthy, 2002; Wilcock et al., 2001), Venditti et al. (2010a, 2010b) showed that fine gravel pulses could mobilize coarser gravel transport, in an aggradation case due to fine sediment feeding.

Comparatively, few computational models of graded bed load transport have been tested against degradation cases. This is because observed data of degradation cases are meagre and generally suffer from limitations. Specifically, previous observed data concerning the flow, sediment transport and bed evolution for degradation cases were insufficient for setting up mathematical modelling (Dietrich et al., 1989; Pender et al., 2001), as stage data was not available at the downstream end for specifying boundary conditions. Likewise, previous observed data featured too much scattering, lower sediment transport rates and minor changes in bed surface composition (e.g., Fuller, 1998; Willetts et al., 1998). Other studies focused on the effects of cohesive clay on gravel and/or sand in terms of the incipient motion (Kothyari & Jain, 2008) and transport in degradation cases (Jain & Kothyari, 2009; Kothyari & Jain, 2010). Further, previous experimental studies on degradation conditions did not include cases using the same uniform sediments that constitute the graded sediment samples (Ashida & Michiue, 1971; Dietrich et al., 1989; Fuller, 1998; Jain & Kothyari, 2009; Kothyari & Jain, 2010; Pender et al., 2001; Willetts et al., 1998).

These aspects constitute the basic impediments to a clear understanding of the fractional bed load transport in a mixture as compared against its counterpart of uniform sediment in degradation cases. Practically, understanding graded sediment transport in degradation cases is critical for the assessment of the scour processes downstream dams or between sills (Ashida & Michiue, 1971;
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Tregnaghi et al., 2009; Yang et al., 2007). The need for systematic observed data is evident of flow, graded sediment transport and bed evolution in degradation cases.

Unlike previous experimental studies focusing on the development of amour layers, which were based on statistical analyses of grain-scale bed topography and composition (Curran & Waters, 2014; Mao et al., 2011; Marion et al., 2003), the present work aimed to generate new experimental data of flow, graded bed load transport and bed evolution in a degradation channel to support mathematical river modelling. Flume experiments were conducted in which four sediment beds with differing sand/gravel contents were scoured by one of five flow discharges. The four sediments beds were composed of well-sorted sand and/or beads, with sand contents of 0%, 47%, 78% and 100% respectively. The beads were of gravel size and hereafter referred to as gravel for convenience. The densities of the gravel and sand were 2390 kg/m³ and 2650 kg/m³ respectively. A total of 20 runs of clear-water scour experiments were carried out. For each run, detailed measurements of the flow, bed elevation, fractional transport rates and bed surface composition were conducted. The fractional transport rates of gravel and sand in cases of graded sediments were compared with those of uniform sediments in the same flow discharges to reveal the interactions between gravel and sand in graded bed load sediment transport in a degrading channel.

2. Method

2.1 Sediment

The wide range of grain sizes in natural graded sediments may considerably complicate the transport phenomenon. A viable approach to quantifying graded sediment transport is to divide the bed material into two uniform fractions, i.e., gravel (grain size $D_g > 2$ mm) and sand ($D_s < 2$ mm), each with a representative particle diameter (Almedeij et al., 2006; Kuhnle et al., 2013; Wilcock, 1998; Wilcock et al., 2001). This is followed in designing the present experiments. The sediments
consisted of well-sorted gravel and sand. The gravel, Sample A, was in the range of 2.0 mm to 4.0 mm in diameter. Gravel particles were spherical with a mean specific gravity of 2.39. The sand, Sample B, varied between 0.1 mm and 2.0 mm in diameter, which was sieved by natural sand with a mean specific gravity of 2.65. Sample C and Sample D were made by mixing Samples A and B according to the mass ratio of 1:1 and 1:4 (i.e., the volumetric proportion of sand was 47% and 78%) respectively. Samples A, B, C and D were successively laid in the flume to compose four different sediment beds. The physical characteristics of the bed sediments are listed in Table 1, and the size distribution is shown in Fig. 1. Particularly, Sample A was in white, whilst Sample B was in yellow. The difference in color in the sediments allowed the employment of the photographic method for the measurement of bed surface size distribution (Adams, 1979; Wilcock & McArdell, 1993).

Table 1. Physical characteristics of bed sediments

<table>
<thead>
<tr>
<th>Sample</th>
<th>Material</th>
<th>Median size $d_{50}$ (mm)</th>
<th>Color</th>
<th>Density (kg/m$^3$)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100% Gravel</td>
<td>3.1</td>
<td>White</td>
<td>2390</td>
<td>0.426</td>
</tr>
<tr>
<td>B</td>
<td>100% Sand</td>
<td>0.67</td>
<td>Yellow</td>
<td>2650</td>
<td>0.412</td>
</tr>
<tr>
<td>C</td>
<td>53% gravel, 47% sand</td>
<td>2.0</td>
<td>/</td>
<td>2513</td>
<td>0.420</td>
</tr>
<tr>
<td>D</td>
<td>22% gravel, 78% sand</td>
<td>0.8</td>
<td>/</td>
<td>2593</td>
<td>0.415</td>
</tr>
</tbody>
</table>

Fig. 1. Size distribution by weight of bed sediments

2.2 Transport and hydraulic measurements

The experiments were conducted in a flume that is 35 m long, 1.2 m wide and 0.8 m deep, as illustrated in Fig. 2. A 20 m long fixed bed made by cement was placed at the upstream part of the flume, followed by the 12 m long loose sediment bed in the working section. At the downstream end of the sediment bed, there was a 0.02 m long iron rigid bed to prevent local scour due to
waterfall into the sediment trap. Downstream the working section was a 1 m long, full-width sediment trap featuring two valves (Fig. 2d). The sediment in the trap was collected every 20 minutes, without the need to shut the flow off. This was accomplished by operating the two valves in the sediment trap in a particular manner. Initially, Valve A was open and Valve B was closed (as shown in the picture to the left in Fig. 2d). All the sediments that fallen into the trap in 20 minutes were accommodated in between Valves A and B. At 20 minutes, Valve A was closed while Valve B was open so that the sediments trapped in the 20-minute period can be collected (as shown in the picture to the right in Fig. 2d). During this period of operation that was much shorter than 20 minutes, the sediments trapped were placed above Valve A. As soon as the collection is finished, Valve A is open and Valve B is closed, and it is ready for trapping sediments in the next 20 minutes. Once the sediment collected in each 20-minute period was later dried and weighed, the amount of sediment transported through the cross section immediately upstream the trap was obtained. For graded sediment, the sediment is also sieved. When it is divided by the time interval (20 minutes), one yields the sediment transport rate during the period. Based on these data, one can readily calculate the average sediment transport rate during the whole period of each run of experiment.

The sidewalls of the flume were mounted with four automatic water-level probes and two automatic terrain monitor (Fig. 2), and a computer was deployed to process the water level and bed elevation data transmitted from the probes. The transient water level was measured at the centre of the channel at four cross sections. The tracking speed of the water-level probes was set at 100 mm/s, and the corresponding measurement error was within ±0.5 mm as the sampling frequency is set at 2 Hz. Each automatic terrain monitor measured the bed elevations at 13 points evenly distributed across a cross section in a period of about 2 minutes, with a measurement error of 0.6 mm. Thus, the bed elevations at two cross sections were continuously measured during the course of the experiments. The final bed elevation was measured using the automatic terrain monitors at the end of each run of the experiments, at cross sections 20 cm apart in the first 4 m
reach downstream the inlet of the mobile-bed section (Fig. 2), and in the remaining reach at cross sections 40 cm apart. At each cross section, the bed elevations at 13 points evenly distributed laterally were measured. An electromagnetic flow meter was emplaced at the inlet of the flume to determine the inflow discharge, and the flow regime could be controlled by means of a tailgate at the outlet of the flume.

**Fig. 2.** Experimental setup (a. perspective view; b. top view; c. front view; d. sediment trap)

### 2.3 Bed surface composition

At the end of each run of the experiments, the bed surface composition was measured by two methods. The first was the traditional volume-by-weight method commonly used in bulk sampling and sieve analyses, which involved the bed surface excavation. The second was the grid-by-number method, which has been shown to be equivalent to the volume-by-weight method (Kellerhals & Bray, 1971). This was accomplished by projecting photographs of the bed onto a grid, and tallying the grain color (hence sand or gravel) falling on the grid. Each photograph covered a bed section 1 m wide and 1.2 m long, while the remaining 10 cm on each side of the flume was not photographed. Ten adjacent photographs provided continuous downstream coverage of the 12 m long working section of the channel. For each photograph, 500×600 points were counted and analyzed by computer, the cross-stream and downstream separations between grid points were 2 mm, and the diagonal separation between grid points was 2.8 mm. This spacing is smaller than the largest size on the bed. Wilcock and McArdell (1993) suggested that a conservative estimate of the error in measuring bed surface composition for this method was ±30%, and the actual error should be considerably smaller.

To investigate how the bed surface composition changes in time during the course of the experiments, the bed surface in a particular section of the channel, i.e., $2.4 < x < 3.6$ m, was
photographed every 1 hour and the gravel and sand proportions were determined by the grid-by-number method. This complements the measurement of bed surface composition at the end of each run of the experiments. The photographs were taken through the flowing water, without shutting the flow off and disturbing the experiment. In principle, the photographs so taken may capture the moving bed load sediment particles, in addition to those on the bed surface. Yet, it is hard to distinguish these moving particles from those on the bed surface, though moving particles were scarce by visual observation. Thus uncertainty is inevitable concerning the observed bed surface size distribution attained by this method.

2.4 Experimental procedure

Prior to each run, the slope of the sediment bed was leveled to 0.003, which was the same slope as the fixed bed upstream. Then the tailgate was raised, and the flume was filled with water from the downstream end. After this, the pump was started, the tailgate was opened, and a relatively small inflow was maintained to establish a steady initial condition. The small inflow was so weak that no sediment could be transported. Afterwards the flow discharge was increased to the desired value and held constant. Then, the experiment began. No sediment was recycled or fed during each run, and each run lasted for 7 hours. This period was determined after a trial-and-error procedure, during which there were sufficiently strong bed deformation and changes in bed surface composition in all the runs of experiment. This is sensible to better support mathematical river modelling studies, especially when it is necessary to distinguish the effects of the flow and sediment properties from the uncertainty arising from empirical relationships introduced to close the model equations.

A total of 20 runs were carried out as summarized in Table 2. Runs A1-A5 relate to cases of uniform gravel, and Runs B1-B5 represent cases of uniform sand. Runs C1-C5 employ Sample C as sediment bed, thus the volumetric proportion of sand is 47%. For Runs D1-D5, the sediment bed is made up by Sample D, with which the volumetric sand content is 78%. In Table 2, the
$x$-axis direction is consistent with the direction of flow, and the cross section of the junction of fixed bed and sediment bed is set to be $x = 0$ m. $q$ is the designed unit-width flow discharge, $h$ and $q_{bs}$ are respectively the flow depth and unit-width volumetric transport rate of gravel ($q_{bg}$) or sand ($q_{bs}$) averaged over the duration of the experiments (i.e., 7 hours).

Table 2. Summary of experiments

<table>
<thead>
<tr>
<th>Run</th>
<th>$q$ ($m^2/s$)</th>
<th>Water slope</th>
<th>$h$ (m)</th>
<th>$q_{bg}$ ($m^2/s$)</th>
<th>$q_{bs}$ ($m^2/s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t = 0$</td>
<td>$t = 7$ h</td>
<td>$x = 0$ m</td>
<td>$x = 12$ m</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>0.01</td>
<td>0.00284</td>
<td>0.00287</td>
<td>0.025</td>
<td>0.026</td>
</tr>
<tr>
<td>A2</td>
<td>0.015</td>
<td>0.00272</td>
<td>0.00267</td>
<td>0.031</td>
<td>0.033</td>
</tr>
<tr>
<td>A3</td>
<td>0.02</td>
<td>0.00289</td>
<td>0.00292</td>
<td>0.037</td>
<td>0.04</td>
</tr>
<tr>
<td>A4</td>
<td>0.025</td>
<td>0.00284</td>
<td>0.00285</td>
<td>0.043</td>
<td>0.045</td>
</tr>
<tr>
<td>A5</td>
<td>0.03</td>
<td>0.00283</td>
<td>0.00294</td>
<td>0.048</td>
<td>0.05</td>
</tr>
<tr>
<td>B1</td>
<td>0.01</td>
<td>0.00305</td>
<td>0.00270</td>
<td>0.025</td>
<td>0.026</td>
</tr>
<tr>
<td>B2</td>
<td>0.015</td>
<td>0.00294</td>
<td>0.00277</td>
<td>0.031</td>
<td>0.033</td>
</tr>
<tr>
<td>B3</td>
<td>0.02</td>
<td>0.00318</td>
<td>0.00284</td>
<td>0.037</td>
<td>0.04</td>
</tr>
<tr>
<td>B4</td>
<td>0.025</td>
<td>0.00287</td>
<td>0.00304</td>
<td>0.043</td>
<td>0.045</td>
</tr>
<tr>
<td>B5</td>
<td>0.03</td>
<td>0.00298</td>
<td>0.00298</td>
<td>0.048</td>
<td>0.05</td>
</tr>
<tr>
<td>C1</td>
<td>0.01</td>
<td>0.00293</td>
<td>0.00287</td>
<td>0.025</td>
<td>0.026</td>
</tr>
<tr>
<td>C2</td>
<td>0.015</td>
<td>0.00281</td>
<td>0.00277</td>
<td>0.031</td>
<td>0.033</td>
</tr>
<tr>
<td>C3</td>
<td>0.02</td>
<td>0.00270</td>
<td>0.00276</td>
<td>0.037</td>
<td>0.04</td>
</tr>
<tr>
<td>C4</td>
<td>0.025</td>
<td>0.00285</td>
<td>0.00286</td>
<td>0.043</td>
<td>0.045</td>
</tr>
<tr>
<td>C5</td>
<td>0.03</td>
<td>0.00295</td>
<td>0.00274</td>
<td>0.048</td>
<td>0.05</td>
</tr>
<tr>
<td>D1</td>
<td>0.01</td>
<td>0.00304</td>
<td>0.00287</td>
<td>0.025</td>
<td>0.026</td>
</tr>
<tr>
<td>D2</td>
<td>0.015</td>
<td>0.00270</td>
<td>0.00275</td>
<td>0.031</td>
<td>0.033</td>
</tr>
<tr>
<td>D3</td>
<td>0.02</td>
<td>0.00276</td>
<td>0.00274</td>
<td>0.037</td>
<td>0.04</td>
</tr>
<tr>
<td>D4</td>
<td>0.025</td>
<td>0.00276</td>
<td>0.00271</td>
<td>0.043</td>
<td>0.045</td>
</tr>
<tr>
<td>D5</td>
<td>0.03</td>
<td>0.00270</td>
<td>0.00293</td>
<td>0.048</td>
<td>0.05</td>
</tr>
</tbody>
</table>

3. Results

3.1 Water flow and sediment transport

In order to generate sufficient dataset that can be exploited to support the development and testing of mathematical river models, detailed measurements of stage, fractional sediment transport rate, bed elevation and bed surface composition were collected for each run. Here, we present the
results for Run C4 to illustrate the processes, which are typical of other runs. The complete dataset for all runs is available upon request to support other investigations.

Fig. 3 shows the stage hydrographs for Run C4. It can be seen that the observed stage gradually increased from an initial small value to a nearly steady level in about 2 minutes, which is consistent with the designed inflow process (see section 2.4 Experimental procedure). The observed stage from the four water-level probes placed along the 12 m long sediment bed can be used to evaluate the water surface slope, and the observations of stage variation at $x=0$ m and $x=12$ m are essential for specifying boundary conditions for mathematical river modeling.

Fig. 4(a) illustrates the variation of the cumulative volume of bed load for Run C4. It can be found that after about 180 minutes, the cumulative volume increases linearly. This essentially indicates that the bed load transport rate has reached constant (Fig. 4b).

**Fig. 3.** Observed stage at different cross sections for Run C4

**Fig. 4.** Bed load transport for Run C4: (a) total volume; (b) transport rate averaged in 20-minute intervals

### 3.2 Bed elevation

Fig. 5 shows the measured bed elevation for Run C4. Significant degradation is spotted (Fig. 5a, b, c), yet the scour was mainly confined to the upstream part ($x<7$ m) of the sediment bed section and is essentially negligible downstream. When testing a mathematical river model, a final bed profile is usually insufficient. In the present work, the bed elevations at two cross sections, $x=2.0$ m and $x=6.0$ m were measured every ten minutes (Fig. 5d), which is useful in calibrating and testing mathematical models.
Fig. 5. Bed elevation for Run C4: (a) initial bed; (b) final bed; (c) cross section averaged initial and final bed elevation; and (d) time variation of cross section averaged bed elevation at \( x = 2.0 \) m and \( x = 6.0 \) m.

The cross section averaged final bed elevation for all the 20 runs are plotted in Figs. 6 and 7. From Fig. 6, it can be seen that for a specific sediment sample, the degradation enhanced with the increase of the inlet flow discharge. Under a specific unit-width flow discharge (Fig. 7), the degradation for the four sediment samples generally follows the rule: Sample A < Sample C < Sample D < Sample B, indicating that the transport rate increases with the increase of sand content in the sediment bed.

Fig. 6. Cross section averaged final bed elevation in relation to different inflow discharges for (a) Sample A, (b) Sample B, (c) Sample C, and (d) Sample D.

Fig. 7. Cross section averaged final bed elevation in relation to different sediment beds under (a) \( q = 0.01 \) m\(^2\)/s, (b) \( q = 0.015 \) m\(^2\)/s, (c) \( q = 0.02 \) m\(^2\)/s, (d) \( q = 0.025 \) m\(^2\)/s, and (e) \( q = 0.03 \) m\(^2\)/s.

3.3 Bed surface composition

To evaluate the bed surface composition sampled for cases of graded sediment transport, \( F_s \) is introduced to represent the volumetric proportion of sand \((F_s)\) or gravel \((F_g)\) in the bed surface. Fig. 8 shows the variation of the bed surface composition of Run C4. During the degrading process, the bed surface coarsened considerably (Fig. 8). Longitudinally, the bed coarsening
extended to the whole sediment bed section of the channel within 7 hours and the final bed coarsened roughly uniformly as compared to the initial bed (Fig. 8a). Temporally, the bed within subsection 2.4<x<3.6 m coarsened in time (Fig. 8b). The longitudinally uniform coarsening renders it appropriate to evaluate the whole-section averaged coarsening as function of flow discharge. In this sense, the bed surface of the whole sediment bed was significantly coarsened, as the percent gravel $F_g$ and median size $d_{50}$ of the final bed are obviously larger than those of the initial bed (Fig. 9). Further, it can be observed from Fig. 9 that $F_g$ and $d_{50}$ are relatively insensitive to the flow discharge but vary systematically with different initial beds, which is in accordance with the finding of Wilcock et al. (2001) for equilibrium cases. Therefore the armor evolution with flow strength and transport rate is subtle not only for equilibrium conditions (Wilcock et al., 2001) but also for degradation conditions (the present work).

**Fig. 8.** Bed surface composition of Run C4: (a) percent (volume) gravel on the initial and final bed surface; (b) variation of percent (volume) gravel ($F_g$) and sand ($F_s$) on the bed surface within subsection 2.4<x<3.6 m

**Fig. 9.** Bed coarsening during degradation as characterized by (a) percent gravel on the bed surface and (b) median grain size of the bed surface

### 3.4 Bed load sediment transport

Fig. 10 shows the scaled dimensionless bed load transport rate $\Phi/f_i$ versus Shields number $\theta$ for gravel and sand averaged over the whole period of the experiments (7 hours), where $f_i$ is the
initial proportion of sand \((f_s)\) and gravel \((f_g)\) in the sediment bed, \(\Phi = \frac{q_{bi}}{\sqrt{(s-1)gd_i^3}}\), \(s\) is the ratio of sediment density to that of water, \(g\) is the gravitational acceleration, \(d_i\) is the median size of gravel \((d_g)\) or sand \((d_s)\), \(\theta = u^2/(s-1)gd_i\) is the shields number, \(u_s = \sqrt{gRS}\) is the shear velocity, \(R\) is the hydraulic radius of the flow, and \(S\) is the slope of the water surface. The bed shear velocity is so calculated as the flow at the cross section immediately upstream the sediment trap can be considered nearly steady and uniform (Fig. 3). It is clearly shown in Fig. 10 that in relation to the same Shields number, the scaled dimensionless fractional transport rate of gravel in cases of graded sediments (Runs C1-C5 and D1-D5) is higher than that in cases of uniform gravel (Runs A1-A5). In contrast, the scaled dimensionless transport rate of sand in cases of graded sediments (Runs C1-C5 and D1-D5) is lower than that in cases of uniform sand (Runs B1-B5). On the other hand, by comparison of the cases of graded sediments (Runs C1-C5 and D1-D5), it is shown that the scaled dimensionless transport rates of Runs D1-D5 are higher than those of Runs C1-C5 for both gravel and sand in accord with a specific Shields number.

**Fig. 10.** Scaled dimensionless bed load transport rate versus Shields number for fractional transport of gravel and sand

Fig. 11(a) illustrates the time variation of the total dimensionless bed load transport rates (gravel plus sand) for Runs A3, B3, C3 and D3 with the same flow discharge 0.02 m²/s. The variations for other runs with different discharges are qualitatively the same, thus not shown. It is seen in Fig. 11(a) that the dimensionless transport rates of Runs C3 and D3 are within the range of Runs A3 and B3, and as the sand content increases, the total transport rate increases (i.e., Run
Fig. 11(b) represents the scaled time variation of the dimensionless bed load transport rates for each fraction (gravel or sand). It is shown that for gravel, the scaled dimensionless fractional transport rate increases as sand content increases (Runs A3>C3>D3), while for sand, the scaled dimensionless fractional transport rate decreases as gravel content increases (Runs B3>D3>C3).

Generally, the finer sand particles tend to hide behind and between the coarser gravel particles, while the coarser gravel particles are more exposed to the hydrodynamic forces (Einstein, 1950). As a result, sand in a sand-gravel mixture is more difficult to set into motion than the same sized uniform sand, whereas the incipient motion of gravel is much easier than its uniform equivalents (Kuhnle, 1993; Wilcock, 1998; Xu et al., 2008). It is also established that the fractional transport rates of gravel and sand are greatly affected by their contents in the mixture. Iseya and Ikeda (1987) showed that gravel transport rates could be maintained or even augmented in the presence of additional sand. Afterwards, Wilcock et al. (2001) found that as sand content increases, the fractional transport rate of gravel is greatly increased, and the rate of increase in sediment could not simply be explained from the decrease of particle size. Recently, the measurements of Kuhnle et al. (2013) indicated that an increase in the amount of sand led to increase in gravel transport by orders of magnitude. For aggradation cases due to sediment feeding, Venditti et al. (2010a, 2010b) examined the effects of fine gravel pulses on gravel transport and suggested that, in general, finer sediment (not just sand) could mobilize coarser sediment and expressions for the influence of sand on bed mobility need to be generalized on the basis of grain ratios. Intuitively, the promoting and hindering impacts should be functioning in degradation cases, just as in equilibrium (Kuhnle, 1993a, 1993b; Kuhnle et al., 2013; Wilcock & Crowe, 2003; Wilcock & Kenworthy, 2002; Wilcock et al., 2001) and aggradation (Venditti et al., 2010a, 2010b) cases. However, the authors are not aware of previous observed data for degradation cases that confirms the occurrence of promoting and hindering. In this respect, the present work facilitates new observed data that clearly shows promoting and hindering impacts in a degrading channel (Figs. 10, 11).
Fig. 11. Variation of (a) the dimensionless bed load transport rate, and (b) the scaled fractional dimensionless bed load transport rate for Runs A3, B3, C3 and D3

3.5 Quantifying promoting and hindering impacts - the promoting and hindering factors

To date, the promoting and hindering impacts for equilibrium cases has been evaluated in terms of the critical shear stress for incipient motion of sediment (Wilcock & Crowe, 2003; Wilcock & Kenworthy, 2002). However, the critical shear stress is hard to pinpoint and succinctly cannot be directly measured. More critically, it has often been estimated in accord with a significantly low transport rate by extrapolating the measured transport rates under different discharges, which inevitably bears much uncertainty. Therefore, an alternative approach is warranted for evaluating the promoting and hindering impacts in graded bed load transport. Here the impact factors are defined based on fractional sediment transport rates that are directly observed.

From the above analysis (Figs. 10 and 11), it is found that with the same proportion and flow conditions, the fractional transport rates of gravel in cases of graded sediments are higher than those in cases of uniform gravel, which indicates that sand promotes the transport of gravel.

Herein, the impact factor $F_{sg}$ is introduced to quantify the effects of sand on gravel transport. Physically, under the same flow discharge, the gravel transport rates in cases of respectively graded sediments and uniform gravel are proportional to the content of gravel, and at the same time the effects of sand on gravel transport can be quantified by the impact factor $F_{sg}$. Therefore, one has

$$\frac{q_{bgj}}{q_{bgug}} = \frac{f_{sj}}{f_{sug}} F_{sgj}$$

This leads to the expression of the impact factor
where the subscript \( j \) denotes cases of graded sediments with different gravel/sand content, the subscript \( ug \) denotes uniform gravel. Obviously, the gravel content \( f_{ug} \) is equal to 1 in cases of uniform gravel.

Similarly, the impact factor \( F_{gs} \) is introduced to characterize the effects of gravel on sand transport

\[
F_{gsj} = \left( \frac{q_{bsj}}{f_{s}} \right) / \left( \frac{q_{bsu}}{f_{sus}} \right)
\]

where the subscript \( us \) denotes uniform sand, and obviously \( f_{sus} = 1 \).

Fig. 12 illustrates the variation of the impact factors with flow discharge for Runs C1-C5 and Runs D1-D5. Generally, the value of \( F_{sg} \) is greater than 1, while the value of \( F_{gs} \) is less than 1.

This indicates that compared with uniform bed load sediment transport, the sand in graded sediment transport exerts a promoting effect on the transport of gravel, and in contrast the gravel has a hindering effect on sand transport.

Also, it is shown in Fig. 12 that with the decrease of flow discharge, \( F_{sg} \) increases and \( F_{gs} \) decreases. This clearly characterizes that the promoting and hindering impacts become more pronounced as the flow discharge decreases. Moreover, the value of \( F_{sg} \) for Runs C1-C5 (47% sand) is smaller than that of Runs D1-D5 (78% sand), indicating that the promoting impact increases as sand content increases. Meanwhile, the value of \( F_{gs} \) for Runs C1-C5 (53% gravel) is smaller than that of Runs D1-D5 (22% gravel), thus the hindering impact increases with the increase of gravel content.

It is noted that the sizes of the gravel and sand used in the present experiments for degradation
cases are disparate, while their densities are distinct (Table 1). It follows that the promoting and
hindering effects identified from the observed transport rates are contributed not only by their
sizes but also by their densities. One might argue that the density effect could be isolated by
means of hydraulic similitude principle, which evokes the use of a bed load transport formula.
However, this is inherently problematic because existing bed load transport formulae (e.g.,
Einstein, 1950; Engelund & Hansen, 1967; Meyer-Peter & Müller, 1948) have been derived for
equilibrium transport cases under steady and uniform flows, whilst the present experiments
featured non-equilibrium bed load transport under non-uniform flows; and also none of existing
bed load transport formulae is universally valid. Therefore, refined mathematical modelling of the
fluvial flow-sediment-morphological processes is warranted in evaluating the new experimental
datasets, which is reserved for investigations in the future. In this regard, the recent model
developments (e.g., Hu et al., 2014; Qian et al., 2015) can be exploited with appropriate
modifications to incorporate the density effect.

Fig. 12. Variation of impact factors with different flow discharges

4. Implications
It is now revealed by the present flume experiments that the promoting and hindering impacts are
functioning in graded bed load transport in degrading channels, complementing previous studies
on equilibrium (Kuhnle, 1993a, 1993b; Kuhnle et al., 2013; Wilcock & Crowe, 2003; Wilcock &
Kenworthy, 2002; Wilcock et al., 2001) and aggradation (Venditti et al., 2010a, 2010b) cases. This
has important implications for fluvial processes subject to land, water and ecological resources
management. Human and natural activities, such as fire, logging, flow diversion, urban and rural
development, and climate change that can directly affect runoff generation (Lane et al., 2007),
would change the supply of sand or gravel to alluvial rivers. Consequently, these rivers may suffer
severe morphological changes as a result of the dramatic increase or decrease in sediment transport rate, especially at lower flows because of the pronounced promoting and hindering factors (Fig. 12). One of the most telling cases concerns the decrease of sediment transport in Goodwin Creek (Kuhnle et al., 1996). The decrease in cultivated land use directly reduced the supply of fine sediment, which subsequently caused the transport of gravel and total sediment load to be diminished (Kuhnle et al., 1996). Arguably, the decrease of sediment delivery by the Yellow River constitutes another case (Wang et al., 2010). Though many studies have addressed this issue (e.g., Miao et al., 2010), it remains incompletely understood due to the complexity of the Yellow River system. From the present work, it is argued that the decrease of fine sediment supply from the Loess Plateau due to effective soil-conservation practices (e.g., forestation and grass-planting) and reduced agricultural activities may have considerably reduced the coarse sediment transport, and consequently the total sediment load.

5. Conclusion

A total of 20 runs of clear-water bed degradation experiments are conducted under the same range of flow discharge using four sediment samples, i.e., uniform 100% gravel, uniform 100% sand, 53% gravel plus 47% sand, and 22% gravel plus 78% sand. The new observed data are sufficient for calibrating and testing computational models built on shallow water hydrodynamic equations. The present observed data reveals that in degradation cases, gravel exerts a hindering impact on sand transport, whilst sand exhibits a promoting impact on gravel transport. Also, the promoting and hindering impacts enhance significantly (by orders of magnitude) with the decrease of flow discharge in degradation cases. With respect to the promoting and hindering effects, the present work on degradation situations complements previous studies on equilibrium and aggradation cases. Human activities and climate change may alter sand or gravel inputs into alluvial rivers, and therefore graded bed load transport. Consequently, these rivers may experience severe morphological changes.
Declaration: The raw experimental data can be made available upon request to support investigations in the general context of river dynamics.

Acknowledgement

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Notation

The following symbols are used in this paper:

\[ \begin{align*}
D_g &= \text{sediment diameter of gravel}; \\
D_s &= \text{sediment diameter of sand}; \\
d_{s0} &= \text{sediment median size}; \\
d_g &= \text{median size of gravel}; \\
d_s &= \text{median size of sand}; \\
F_g &= \text{proportion of gravel in the bed surface}; \\
F_{gs} &= \text{impact factor represent the effects of gravel on sand}; \\
F_s &= \text{proportion of sand in the bed surface}; \\
F_{sg} &= \text{impact factor represent the effects of sand on gravel}; \\
f_g &= \text{initial proportion of gravel in the sediment bed}; \\
f_s &= \text{initial proportion of sand in the sediment bed}; \\
g &= \text{gravitational acceleration};
\end{align*} \]
$h =$ flow depth;

$i =$ subscript denotes gravel or sand;

$j =$ subscript denotes cases of graded sediments with different gravel/sand content;

$q =$ unit-width flow discharge;

$q_b =$ volumetric transport rate;

$q_{bg} =$ volumetric transport rate of gravel;

$q_{bs} =$ volumetric transport rate of sand;

$R =$ hydraulic radius of the flow;

$S =$ slope of the water surface;

$s =$ ratio of sediment density to that of water;

$u_{g} =$ subscript denotes cases of uniform gravel;

$u_{s} =$ subscript denotes cases of uniform sand;

$u_* =$ bed shear velocity;

$x =$ streamwise coordinate;

$\theta =$ Shields number; and

$\Phi =$ dimensionless bed load transport rate.
References


List of Figure Captions

Fig. 1. Size distribution by weight of bed sediments

Fig. 2. Experimental setup (a. perspective view; b. top view; c. front view; d. sediment trap)

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Fig. 4. Bed load transport for Run C4: (a) total weight; (b) transport rate averaged in 20-minute intervals

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Fig. 6. Cross section averaged final bed elevation in relation to different inflow discharges for (a) Sample A, (b) Sample B, (c) Sample C, and (d) Sample D

Fig. 7. Cross section averaged final bed elevation in relation to different sediment beds under (a) \( q = 0.01 \text{ m}^2/\text{s} \), (b) \( q = 0.015 \text{ m}^2/\text{s} \), (c) \( q = 0.02 \text{ m}^2/\text{s} \), (d) \( q = 0.025 \text{ m}^2/\text{s} \), and (e) \( q = 0.03 \text{ m}^2/\text{s} \)
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Fig. 9. Bed coarsening during degradation as characterized by (a) percent gravel on the bed surface and (b) median grain size of the bed surface

Fig. 10. Scaled dimensionless bed load transport rate versus Shields number for fractional transport of gravel and sand

Fig. 11. Variation of (a) the dimensionless bed load transport rate, and (b) the scaled fractional dimensionless bed load transport rate for Runs A3, B3, C3 and D3

Fig. 12. Variation of impact factors with different flow discharges
<table>
<thead>
<tr>
<th>Sample</th>
<th>Material</th>
<th>Median size $d_{50}$ (mm)</th>
<th>Color</th>
<th>Density (kg/m$^3$)</th>
<th>Porosity</th>
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**Table 2. Summary of experiments**

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<td>$x = 0$ m</td>
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</tr>
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