Relative Transportability for Non-uniform Bed Load Sediment Transport

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Abstract. Clear water scour experiments with a wide range of water discharge were conducted on uniform and non-uniform beds. The fractional transportability in non-uniform runs is compared with that of the same fraction in uniform runs. It is found that in non-uniform runs, the fractional transportability of gravel is greatly promoted compared with that in uniform runs by the same proportion, while the transportability of sand fraction is obviously inhibited. Furthermore, although the transport rate of sand is undoubtedly much greater than that of gravel under the same flow strength in uniform runs, the transport rates of sand fraction and gravel fraction are found to be nearly the same in non-uniform runs.

1. Introduction

The mechanics of sediment transport in alluvial rivers is an important issue in fluvial hydraulics and morphodynamics. Since mid-18th century, this issue has been a hot subject of study, and a lot of inspiring findings put this subject to a new height [1-4]. However, nature will not be so easy for us to understand clearly, and pose a series of impediments to the refinement of further study. Among these obstacles, the transport of non-uniform sediment is absolutely one of the most challenging issues because of the unsteady and random characteristics in its physical process.

Previous researches in the field of sediment transport are mostly focus on the transport of uniform sediments, numerous formulae and mathematical models have been proposed for sediment transport stressing a different aspect of sediment characteristics. Yet, these formulae and models were verified by experimental data with uniform or nearly uniform sediment only, and can only be used as a qualitative estimation for real rivers. The transport mechanism of non-uniform sediment transport is different to that of uniform sediment due to the exchange of different particle size in the suspension and bed material [5-7]. For example, the settling velocity does not vary with the exchange between the suspended and bed material for uniform sediment while the exchange between the suspended and bed material changes the size distributions of suspended and bed material under non-uniform sediment transport. As a result, the previous achievements in the study of uniform sediment transport can not be directly applied on the non-uniform sediment transport, and employing the non-uniformity of sediment in the simulation of sediment transport is needed.

During the last several decades, a number of experiments have been performed and lots of numerical models have been proposed for the investigation of sediment transport with a range of

sediment sizes including those of Proffitt and Sutherland (1983), Dietrich et al. (1989), Paola et al. (1992), Parker and Wilcock (1993), Wilcock and McArdell (1993), Lu and Zhang (1993), Yen and Lee (1995), Willetts et al. (1998), Wu (2004), Fischer-Antze et al. (2009), Yang et al. (2010), Viparelli et al. (2010). To a certain extent, these meaningful studies have revealed the mechanics of non-uniform sediment transport [8-19]. However, due to the complex characteristics, the understanding of some fundamental issues is still far from sufficient.

In this work, a total of 15 runs of clear water scour experiments with a wide range of water discharge were conducted. Two fractions of well sorted uniform sand and gravel were employed to compose three kind of sediment bed, including the two uniform fractions respectively, and the non-uniform mixture of these two fractions with mass ratio of 1:1. For each run, coupled observations of flow, bed elevation, transport rate and bed surface composition were collected, and the fractional transportability in non-uniform runs are compared with that of the same fraction in uniform runs, the relative transportability for non-uniform bed load sediment transport is analyzed.

2. Experiments

The sediments used in the experiments consisted of well sorted gravel and sand. The gravel called Sample A was in the range of 2.0 mm to 4.0 mm, particle appearance was spherical or elliptical, and particle material was ceramic with mean specific gravity of 2.39. The sand called Sample B varied in size between 0.1 mm and 2.0 mm which was sieved by natural sand with mean specific gravity of 2.65. Sample C was made by mixing Sample A and B according to the mass ratio of 1:1 and 1:4 (i.e. the volumetric proportion of sand was 47%). Sample A, B, and C were successively laid in the flume to compose four kinds of sediment beds.

The experiments were conducted in a flume, 40 m long, 2.4 m wide and 1.0 m deep. A 15 cm layer of sediment was laid in the flume with the length of 12 m, and before the sediment bed, a 20 m long fixed bed with the same height as sediment bed was employed. The slope of initial sediment bed and fixed bed was set to be 0.003. The clear sidewalls of the flume were mounted with automatic water-level probes and automatic terrain monitor, and a computer was deployed to process the stage and bed elevation data transmitted from the probes. By the end of the sediment bed, 0.02 m of the bed was made rigid to prevent local scour, and then a replaceable sediment trap was equipped for collection of the transported material. 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 end of the flume. No sediment was recycled or feed during each run, and each run lasted 7 hours.

Table 1. Summary of experiments

Run	Sediment bed	Unit discharge, (m^2/s)	Mean flow depth at $x = 0$ m, (m)	Mean flow depth at $x = 12$ m, (m)	Mean transport rate, (g/m/s)	Maximum scour depth, (m)
A1	Sample A	0.02	0.037	0.04	0.94	0.0135
A2	Sample A	0.025	0.043	0.045	2.22	0.0274
A3	Sample A	0.03	0.048	0.05	3.35	0.0349
A4	Sample A	0.035	0.053	0.055	5.41	0.0408
A5	Sample A	0.04	0.057	0.06	8.93	0.0673
B1	Sample B	0.01	0.025	0.026	2.88	0.0122
B2	Sample B	0.015	0.031	0.033	5.01	0.0223
B3	Sample B	0.02	0.037	0.04	5.46	0.0337
B4	Sample B	0.025	0.043	0.045	8.68	0.0550
B5	Sample B	0.03	0.048	0.05	12.40	0.0848
C1	Sample C	0.01	0.025	0.026	0.56	0.0106
C2	Sample C	0.015	0.031	0.033	1.70	0.0237
C3	Sample C	0.02	0.037	0.04	3.86	0.0303

| C4 | Sample C | 0.025 | 0.043 | 0.045 | 5.24 | 0.0515 |
| C5 | Sample C | 0.03 | 0.048 | 0.05 | 7.24 | 0.0791 |

3. Promoting and inhibiting transportability for non-uniform sediment

In order to make quantitatively analysis, we calculate the relative value of transportability for Sample A and B in uniform and non-uniform runs, and introduce the relations

$$\frac{\Phi_A}{\Phi_{C-A}} = \left(\frac{d_A}{d_C}\right)^{-\lambda_1} , \quad \frac{\Phi_B}{\Phi_{C-B}} = \left(\frac{d_B}{d_C}\right)^{-\lambda_2} \tag{1a, b}$$

where $\Phi = q_b / \sqrt{sgd^3}$, q_b is the volumetric sediment transport rate, s is the specific weight, d is the sediment diameter, we can get that the mean value of $\lambda_1 = 2.37$ with the standard deviation 0.94, and the mean value of $\lambda_2 = 0.26$ with the standard deviation 0.046, as the details shown in Table 2. It is noted that in the calculation, the mean transportability for each run is used, and the relative values of each fraction are calculated by same proportion. Figure 1 is the plot of the relation of (1a, b), it shows that for gravel fraction, the transportability in uniform runs is smaller than that in non-uniform runs, while for sand fraction, the transportability is greater in uniform runs than that in non-uniform runs.

Table 2. Relative transportability for fraction A and B in uniform and non-uniform runs

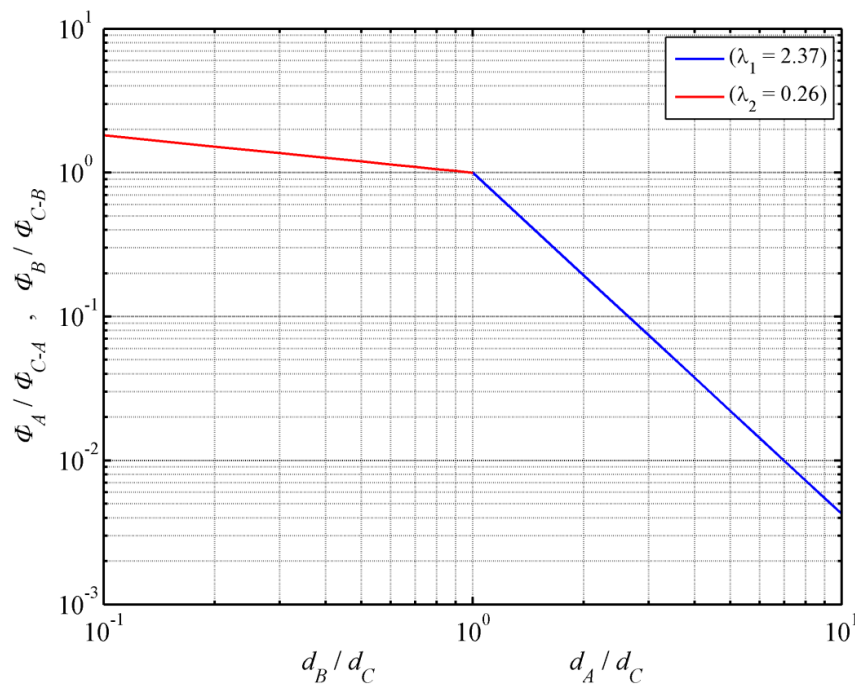| Unit discharge, (m²/s)	Run	Φ_A/Φ_{C-A}	λ_1	Run	Φ_B/Φ_{C-B}	λ_2
0.02	A1, C3	0.2711	3.1785	B3, C3	1.2679	0.2271
0.025	A2, C4	0.4988	1.7870	B4, C4	1.4128	0.3260
0.03	A3, C5	0.4674	1.9357	B5, C5	1.2711	0.2294

Figure 1. Relative transportability versus relative median size for fraction A and B in uniform and non-uniform runs

4. Near-equal transportability for non-uniform sediment

Figure 2 represents the variation of volumetric transport rate for Runs A1, B3, C3. It is found that the transport rate of sand is much greater than that of gravel under the same flow strength in uniform runs, while the transport rates of sand fraction and gravel fraction are found to be nearly the same in non-uniform runs.
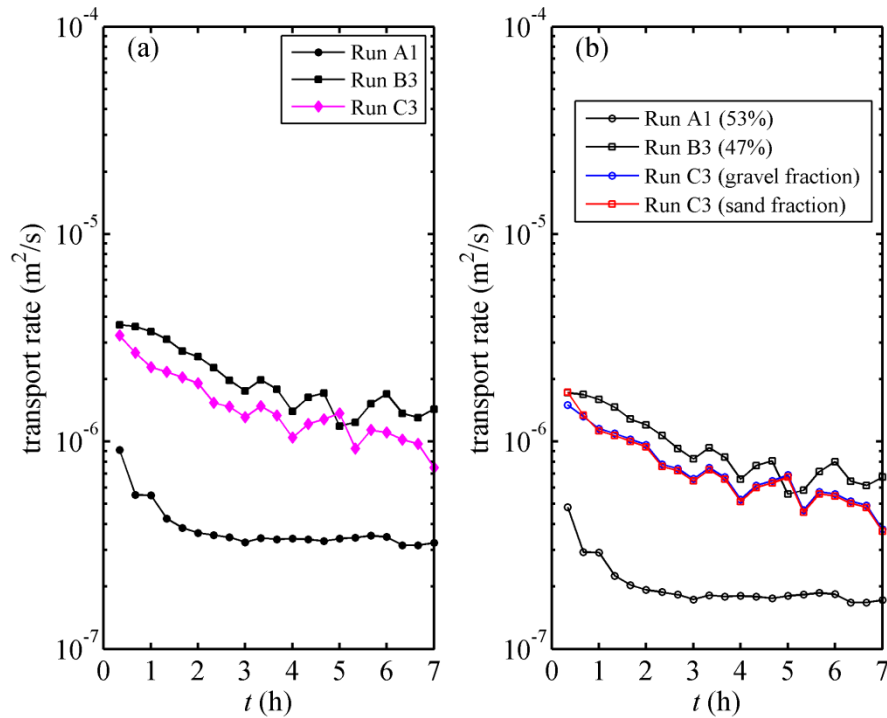

Figure 2. The variation of volumetric transport rate for Runs A1, B3, C3

In order to make quantitatively analysis, we calculate the relative value of transport rate for Sample A and B in uniform and non-uniform runs, and introduce the relations

$$\frac{q_{bA}}{q_{bB}} = \left(\frac{d_A}{d_B}\right)^{-f_1}, \; \frac{q_{bC-A}}{q_{bC-B}} = \left(\frac{d_A}{d_B}\right)^{-f_2} \tag{2a, b}$$

we can get that the mean value of $f_1 = 0.94$ with the standard deviation 0.3, and the mean value of $f_2 = 0.077$ with the standard deviation 0.07, as the details shown in Table 3. Also, the mean transport rate for each run is used, and the relative values of each fraction are calculated by same proportion. Figure 3 is the plot of the relation of (2a, b), it shows that the transport rate of sand is much greater than that of gravel in uniform runs, while the transport rates of sand fraction and gravel fraction are nearly the same in non-uniform runs.

Table 3. Relative transport rate for fraction A and B in uniform and non-uniform runs

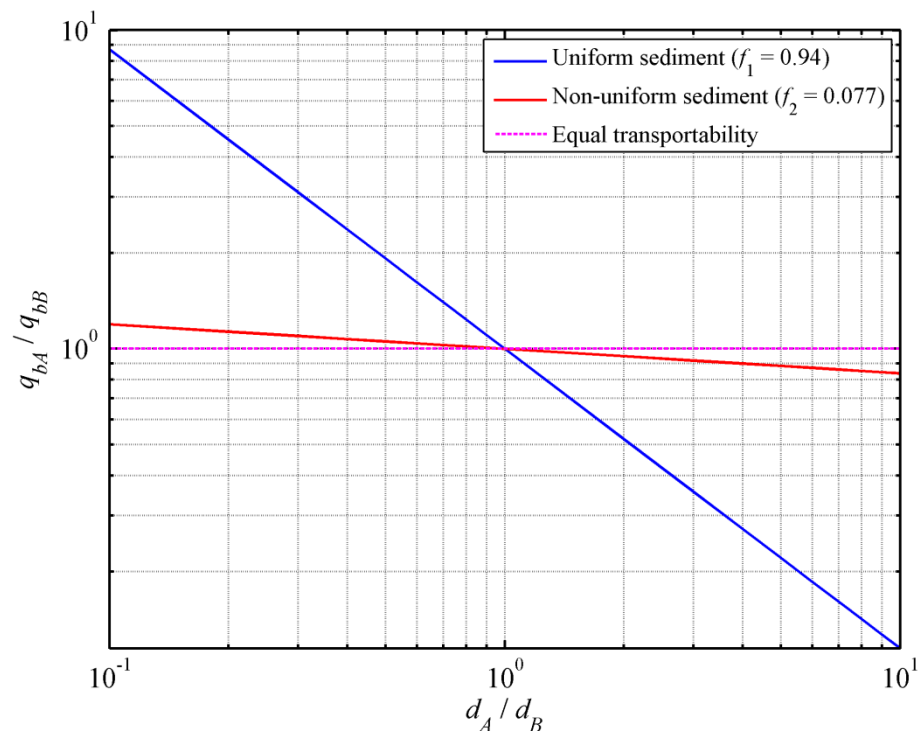| Unit discharge, (m^2/s)	Run	q_{bA}/q_{bB}	f_1	Run	q_{bC-A}/q_{bC-B}	f_2
0.02	A1, B3	0.1904	1.0823	C3	0.8905	0.0557
0.025	A2, B4	0.2831	0.8533	C4	0.8019	0.094
0.03	A3, B5	0.3000	0.8257	C5	0.8159	0.0828

Figure 3. Relative transport rate versus relative median size for fraction A and B in uniform and non-uniform runs

5. Conclusion

Two fractions of narrowly sorted sand and gravel were employed to compose three kind of sediment bed, including the two uniform fractions respectively, and the non-uniform mixture of these two fractions with mass ratio of 1:1. A total of 15 runs of clear water scour experiments with a wide range of water discharge were conducted in two different scale flumes. For each run, coupled observations of flow, bed elevation, transport rate and bed surface composition were collected. As focus on the relative transportability in the present work, the fractional transportability in non-uniform runs are compared with that of the same fraction in uniform runs. It is found that in non-uniform runs, the fractional transportability of gravel is greatly promoted compared with that in uniform runs by the same proportion, while the transportability of sand fraction is obviously inhibited. This indicates that models of transport should account for the influence of promotion and inhibition characteristics in non-uniform sediment transport. Furthermore, the results show that although the transport rate of sand is undoubtedly much greater than that of gravel under the same flow strength in uniform runs, the transport rates of sand fraction and gravel fraction are found to be nearly the same in non-uniform runs. It to some extent corroborates with previous research that equal transportability does exist in non-uniform sediment transport.

Acknowledgement

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