Bed Surface Grain Size Evolution under Unsteady Flow Conditions in a Degrading Channel

Zhijing Li1*, Qiuli Li2, Zhongwu Jin1, Shiming Yao1 and Yinjun Zhou1

1Changjiang River Scientific Research Institute, Wuhan, Hubei, 430010, China
2Hohai University, Nanjing, Jiangsu, 210098, China
*Corresponding author’s e-mail: lzjketty@126.com

Abstract. Laboratory flume experiments were conducted in order to identify the temporal evolution of bed surface grain size properties by unsteady flows under zero sediment feeding conditions. Purposely designed sediment beds were composed by well-sorted gravel and sand, for each case, detailed data of the bed surface composition were collected. It is found that for all cases, the final sediment bed in the whole reach always shows a coarsening feature, and the coarsening process is much more developed near the inlet boundary. Further, the time variation of the percents of gravel and sand are observed increase or decrease alternately during the experiment and finally close to their initial percents. Besides, the experimental results show that there is no direct correlation between the flow unsteadiness and the coarsening degree of the final bed.

1. Introduction
The sediment composition of natural rivers directly affects the speed and evolution of river bed adjusting (Zhao et al. 2005). Bed surface grain size distribution variation related to processes associated with the formation of armour layers in natural gravel-bed rivers has been previously studied (Chris et al. 1992; Guney et al., 2013). In natural rivers, unsteady flow is commonly seen in flood events. Due to the limitation of instruments and equipments, the characteristics of bed surface grain size evolution are extremely difficult to be recovered. Andrews and Erman (1986) collected sediment samples before and after the passage of a flood flow in Sagehen Creek, USA, and found that the bed surface grain size distribution was virtually identical, and after the flood peak had passed, the coarser bed material stays relatively invariant. Wilcock and Detemple (2005) and Parker et al. (2007) found that armour layers remained intact and essentially unchanged during high flows. Also, Mao et al. (2010) and Mao (2012) revealed that bed surface size changed little under stepped hydrographs. These studies qualitatively analyzed the effect of flood process on bed grain size gradation, while the individual effect of unsteadiness and total water work on sediment bed material evolution has not, as yet, been studied in a systematic manner.

In this work, a series of laboratory flume experiments were conducted in order to identify the temporal evolution of bed surface grain size properties by unsteady flows under conditions of sediment starvation (zero sediment feeding). Well-sorted gravel and sand were employed to compose two kinds of sediment beds, for each case, detailed data of the bed surface composition were collected, and the characteristics of the evolution of bed surface grain size under unsteady flow conditions are analyzed.
2. Experiments

2.1. Sediment
Two nearly uniform sediment samples, i.e., samples A (gravel) and B (sand), were used to compose two graded sediment beds, i.e., samples C and D (Table 1). The diameter of Sample A was in the range of 2.0 mm to 4.0 mm, and the mean specific gravity was 2.39. The diameter of Sample B varied between 0.1 mm and 2.0 mm, and the mean specific gravity was 2.65. Sample C and Sample D were made by mixing Samples A and B with the mass ratio of 1:1 and 1:4 (i.e., the volumetric proportion of sand was 47% and 78%) respectively.

Considering the color difference between the yellow sand and white gravel, a grid-by-number method, which has been shown to be equivalent to the volume-by-weight method commonly used in bulk sampling and sieve analyses (Kellerhals and Bray, 1971), was used to determine the bed surface composition (Adams, 1979; Wilcock & McArdell, 1993).

| Samples | Sediment beds | Median size (mm) | Color | Specific gravity | Porosity |
|---------|----------------|-----------------|-------|-----------------|----------|
| A       | Gravel         | 3.1             | White | 2.39            | 0.426    |
| B       | Sand           | 0.67            | Yellow| 2.65            | 0.412    |
| C       | 53% gravel, 47% sand | 2.0 | /     | 2.51            | 0.420    |
| D       | 22% gravel, 78% sand | 0.8 | /     | 2.59            | 0.415    |

2.2. Flume and instruments
Experiments were conducted in a 35 m long, 1.2 m wide and 0.8 m deep flume. The pump system, which was capable of producing controlled and unsteady inflows was controlled by a computer. A fixed bed with a length of 20 m was placed at the front of the loose sediment bed. At the end of the 12 m long working section, there was a 0.1 m long rigid bed which was designed to prevent local scour. Downstream of the working section was a sediment trap. More details of the flume set-up and hydraulic measurements can be found in Li et al., (2016, 2018).

Figure 1. Flume and instruments (a. perspective view; b. top view; c. side view).
2.3. Designed inflows

The purposely designed unsteady hydrographs are shown in Figure 2. All the hydrographs have the same overall hydrograph duration (7 hours) and the same base flow ($q = 0.002 \text{ m}^2/\text{s}$) under which there is no sediment transport. Two unsteady hydrographs, characterized by smooth and continuous sinusoidal curves, which are more representative of the natural hydrographs than the designed stepped or triangle hydrographs. Graf and Suszka (1985) studied the effect of unsteady flow on sediment transport and proposed an unsteadiness parameter $\Gamma_{HG}$ to quantify magnitude of unsteady flows:

$$\Gamma_{HG} = \frac{1}{u_{sh}} \frac{\Delta h}{\Delta T}$$

(1)

where $u_{sh}$ is the friction velocity of base flow, $\Delta h$ is the flow depth difference between peak flow and base flow, $\Delta T$ is the duration of the hydrograph.

Figure 2. Inlet unsteady hydrographs.

A total of 4 experimental cases have been carried out as summarized in Table 2. Cases named begin with “C” use Sample C as sediment bed, and Cases named begin with “D” employ Sample D as sediment bed, thus the volumetric proportion of sand is 47% and 78% respectively. $q_{peak}$ is the peak discharge of the unsteady flows, $V_{total}$ is the total water volume of the hydrograph.

| Case | Sediment bed | Inflow | $q_{peak}$ (m$^2$/s) | $V_{total}$ (m$^3$) | $\Gamma_{HG}$ |
|------|--------------|--------|----------------------|---------------------|--------------|
| CU1  | Sample C     | U1     | 0.018                | 302.4               | 3.93E-05     |
| CU2  | Sample C     | U2     | 0.038                | 604.8               | 7.36E-05     |
| DU1  | Sample D     | U1     | 0.018                | 302.4               | 3.93E-05     |
| DU2  | Sample D     | U2     | 0.038                | 604.8               | 7.36E-05     |

3. Bed surface grain size evolution

Here, $F_i$ represent the volumetric proportion of gravel ($F_g$) or sand ($F_s$) on the bed surface. From Figure 3, which shows the variation of bed surface composition for Case DU2 with unsteady inflow, it can be seen that longitudinally, the final bed surface composition does not change obviously within the reach of $x < 4.8 \text{ m}$ as compared to its initial composition, whilst the remaining reach (i.e., $x > 4.8 \text{ m}$)
m) exhibits a obviously coarsening feature (Figure. 3a). At the same time, a similar phenomenon can be observed from bed elevation. Besides, a non-monotonic trend for the time variation of the percents of gravel and sand is observed within subsection $2.4 < x < 3.6$ m, which increase or decrease alternately during the experiment (Figure. 3b).

Figure 3. Bed surface composition variation for Case DU2: (a) the percent of gravel on the initial and final bed surface; (b) time variation of the percents of gravel ($F_g$) and sand ($F_s$) on the bed surface within the subsection of $2.4 < x < 3.6$ m.

Figure 4 illustrates the percent of gravel on the final bed surface for all the unsteady cases. Generally, the bed surface for the whole reach shows an increase in the percentage of gravel. In terms of coarsening degree, the relative coarsening intensity of bed Sample C is stronger than that of bed Sample D, which is affected by its initial bed sand composition, and the finer the initial bed sand composition is, the more obvious the coarsening is. Further, it is interesting to note that there is no direct correlation between the flow unsteadiness and the coarsening degree of the final bed. With the increase of the flow unsteadiness, the coarsening degree of the bed sand does not increase or decrease significantly.
4. Conclusion
Laboratory flume experiments were conducted in order to identify the temporal evolution of bed surface grain size properties by unsteady flows under conditions of sediment starvation (zero sediment feeding). It is found that for all cases, the final sediment bed always shows a coarsening feature in the whole reach, and the coarsening process is much more developed near the inlet boundary, and non-monotonic trends are observed for the time variation of the percents of gravel and sand, which increase or decrease alternately during the experiment, finally closing to their initial percents. Further, the present results show that there is no direct correlation between the flow unsteadiness and the coarsening degree of the final bed.

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