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Understanding partial bed-load transport: Experiments and stochastic model analysis

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SUMMARY

The complex dynamics of partial bed-load transport in a series of well-controlled laboratory experiments are explored systematically and simulated by a stochastic model in this study. Flume experiments show that the leading front of bed-load on a 20-m-long, mixed-size gravel-bed moves anomalously, where the transient transport rate of the accelerating front varies with the observation time scale. In addition, observations show that moving particles may experience bimodal transport (i.e., coexistence of long trapping time and large jump length) related to bed coarsening and the formation of clusters on a heterogeneous gravel-bed, which is distinguished from the traditional theory of hiding–exposing interactions among mixed-size particles. A fractional derivative model is finally applied to characterize the overall behavior of partial bed-load transport, including the coexistence of the sub-diffusion and non-local feature caused by turbulence and the micro-relief within an armor layer.

1. Introduction

Despite substantial efforts that have been made over the last two decades, our ability to estimate bed-load flux in a turbulent system remains inadequate (Lane, 1947; Lee and Odgaard, 1987). The error in prediction sometimes becomes unacceptable in gravel-bed rivers where the measured transport rates often differ by one to two orders of magnitude from predictions using the standard formulae (Bathurst, 2007; Barry et al., 2004). One of the major obstacles is the poor understanding of the degree to which a river-bed is coarsened or armored (Wilcock and DeTemple, 2005; Barry et al., 2004; Karim and Holly, 1986; Wu et al., 2004). In a mixed-size gravel-bed river, the bed is often sorted such that the surface composition is coarser than the substrate (Whiting and King, 2003; Wilcock and Crowe, 2003; Parker and Sutherland, 1990; Parker, 1990). In addition, cluster structures are often observed on riverbeds composed of particles with a wide range of size distributions, which could significantly alter bed-load transport rates (Strom et al., 2004; Wittenberg and Newson, 2005). The error caused by ignoring this bed-coarsening effect will be most significant if the flow is only able to transport a portion of the particles on the bed surface, i.e., the process of partial transport (Janssen, 2010; Shaheen and Diplas, 2005). Partial transport is the dominant transport condition in many gravel-bed rivers (Wilcock and McArdell, 1997).

In addition, most existing formulae on bed-load transport deal with the average transport rate (mathematic expectation) of major particles as a whole and ignore its variance (Chien and Wan, 1999). This simplification is sometimes acceptable in practice, but not always. Large errors or deviations may arise from the lack of comprehensive explanation of the entire stochastic process. Fig. 1 indicates the bed-load transport on the mixed-size gravel-beds conducted in experiments exhibits substantial randomness, and even sophisticated formulae that include the mechanisms of surface-based transport (e.g., Wilcock and Crowe, 2003) or the hiding-exposure correction (e.g., Wu et al., 2000) cannot satisfactorily estimate the sediment flux. Therefore anomalous particle behaviors, such as coexistence of slower movement due to cluster blocking and faster movement due to the high-speed belts among those clusters (which will be discussed later), should be considered to fully understand the partial transport process of bed-load.

Both super- and sub-diffusive anomalous transport of bed-load have been discussed recently. For example, Nikora et al. (2002), Hill et al. (2010), Bradley et al. (2010), and Martin et al. (2012)

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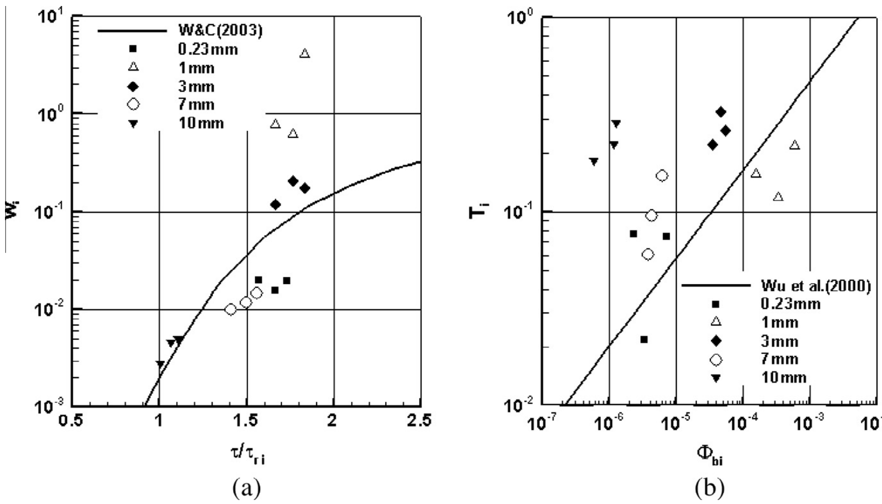

Fig. 1. Fractional transport rates (W_i or Φ_{bi}) as a function of shear stress (τ/τ_{ri} or T_i), (a) measurement vs. a surface-based transport equation, i.e. Wilcock and Crowe (2003); (b) measurement vs. a non-uniform bed-load equation, i.e. Wu et al. (2000).

investigated the super-dispersive displacement of bed-load sediment. These studies further explored the main mechanism of super-dispersion, including the particle inertia within high stream velocities and the mixed displacement for sediment particles with different sizes. In addition, sub-dispersion in sediment particle motion caused by sheltering or burial of particles in the bed has also been discussed (Nikora et al., 2002; Lajeunesse et al., 2010; Martin et al., 2012). Furthermore, the transition from super-dispersion to sub-diffusion was observed and modeled by Martin et al. (2012). Zhang et al. (2012) proposed a tempered random walk model to describe the transition from super-dispersion to sub-dispersion, and the final convergence to Fickian dispersion for bed-load sediment transport.

However, more experiments and stochastic model analysis are still needed to understand the nature of the anomalous bed-load sediment transport. One of the major challenges is the particle size effect on anomalous dynamics, which has not been tackled by previous studies. Besides, none of the aforementioned stochastic studies has investigated the movement of bed-load front, which may be critical for bed-load transport estimation in practice. For instance, sand or silt supply to an armored gravel-bed river might remarkably increase due to events such as wildfire, reservoir flushing, and dam removal (Wilcock et al., 2001). The water-consumers at downstream are highly concerned with the time at which the front of the finer material will arrive at water-intake structures.

In the present study, experimental results provide evidences for the memory and non-locality properties of bed-load transport that may be inherent in a mixed-size gravel-bed during partial transport. In addition, the study offers insights into describing the elusive processes with numerical solutions of the fractional derivative equations (FDEs), in which time fractional derivative corresponds to history memory and spatial fractional derivative refers to non-locality properties of bed-load transport.

2. Experimental setup

Non-uniform bed-load transport and bed coarsening experiments have been conducted by many researchers including Gessler (1970), Little and Meyer (1976), Garde et al. (1977), Sutherland and Williman (1977), Proffitt (1980), Parker et al. (1982), Parker and Wilcock (1993), Wilcock (2001), Diplas and Shaheen (2007), and Mao et al. (2011), but none of these studies has addressed the anomalous dynamics of bed-load transport. As discussed above, anomalous transport tends to arise on a mixed-size gravel-bed during low Shields stress scour, i.e., partial transport. The present experiments are designed to explore the dynamics of bed-load transport by both tracing the displacement of bed-load front with time and examining the spatial distribution of bed-load particles.

In this study, the experimental sand/gravel mixture was prepared by blending grains of five size fractions, i.e. 0.45 mm, 1 mm, 3 mm, 7 mm, and 17 mm, with the proportions shown in Table 1. In terms of the American Geophysical Union (AGU) standard classification (Subcommittee on Sediment Terminology of AGU, 1947), the first fraction falls into the category of fine to medium sand, the second belongs to coarse sand, and the others are gravels. The experiments were conducted in a tilting glass-wall flume with a dimension of 50 m × 1 m × 1.2 m for the length, width and depth (Fig. 2). The effective maximum flume length for sediment transport is 20 m. A carefully leveled bed consisting of a mixture of white color grains was then set to a constant slope of 0.004. The inflow discharge measured by an electromagnetic flow meter varied from 120 l/s to 140 l/s (Table 2).

Instead of a closed system with zero sediment feeding which depends on the initial condition and might result in a "static armor layer" (Mao et al., 2011; Bettess and Frangipane, 2003; Wilcock, 2001; Gessler, 1970), the present experiment was conducted in an open system with continuous sediment feeding (Mao et al., 2011; Diplas and Shaheen, 2007). For example, in the experiment of Run 1, moving grains were collected by a trap placed at the outlet of the flume and weighted in an interval of 15 min and then reloaded at the inlet. After a relatively constant or quasi-equilibrium transport flux was obtained (which was measured at 0.84 g/s), a small portion of the trapped sediment was dried, sieved, and weighted. Meanwhile the sediment circulation was maintained. When obtaining the weight proportions of all the size fractions, we started to feed new sediment particles continuously at the inlet

Table 1
Experimental sand/gravel mixture.

Fractions	d_m (mm)	Weight (%)	Sieve opening sizes (mm)
1	0.45	10	0.25–0.8
2	1.0	15	0.6–1.25
3	3.0	25	1–5
4	7.0	25	5–10
5	17.0	25	15–20