Notes on Bed Load Transport under Unsteady Flow Conditions

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ABSTRACT

Physical modeling and experimental research have become effective methods to study bed load transport phenomena. In this paper, results of flume experiments are presented and discussed in the light of the results of earlier experimental studies found in the literature. Beside its advantages, physical modeling of unsteady bed load transport has a lot of problematic aspects due to a large number of parameters that have to be controlled. Selected aspects, reported in the literature and encountered in the present study, are highlighted in the paper.

KEY WORDS: bed load transport; bed shear stress; flood wave; hysteresis; laboratory experiments; unsteady flow

INTRODUCTION

Bed load transport during flood event has been a significant research topic for last decades (Bombar, 2016; Lee et al., 2004; Mrokowska et al., 2016; Phillips and Sutherland, 1990; Wang et al., 2015). Flood waves intensify sediment transport, trigger morphological changes in rivers, and affect water quality (De Sutter et al., 2001; Julien et al., 2002; Mao, 2012). The problem of bed load transport is still open for systematic research, and it is necessary to derive reliable mathematical expressions for engineering applications.

Bed load transport dynamics is tightly connected with the flow conditions characterized, for example, by flow rate and bed shear stress. Phillips and Sutherland (1990) indicated that under unsteady flow, bed does not react instantaneously to the changing flow. Beside flow conditions, bed load transport depends on sediment availability. Intensified bed load transport is expected for high values of bed shear stress, but only in unarmored conditions where sediment is free to move; otherwise, the maximum sediment transport does not correspond with the maximum bed shear stress (Humphries et al., 2012; Mao, 2012). In real cases, complex processes from grain scale to bulk transport take place, and it is difficult to identify and model all significant processes in a particular case. This leads to high uncertainty of bed load transport predictions.

As Tabarestani and Zarrati (2015) have recently reported, more and more researchers have taken effort to work out methods dedicated to unsteady flow, and resigned from approximating unsteady flow by step-wise steady flow conditions. In that research, laboratory studies are predominant for two reasons. Firstly, experimental conditions are controlled, and impact of unknown processes is reduced; secondly, detailed measurements in natural settings during flood event are not feasible due to safety and practical reasons.

This paper presents advantages and capabilities of laboratory studies, as well as some problematic aspects which have to be kept in mind when planning, performing or analyzing experimental data.

MATERIALS AND METHODS

Experimental set-up

Experiments performed by authors in cooperation with the laboratory of Faculty of Environmental Engineering and Land Surveying, Agricultural University of Krakow will be used to illustrate the meaning and severity of the problems encountered in the studies of sediment transport under unsteady flow conditions. Experiments were carried out in 12 m-long, 0.485 m-wide and 0.60 m-deep flow-recirculating channel. The bed slope was 0.0083. Detailed description of experimental settings has been already published in (Mrokowska et al., 2016)

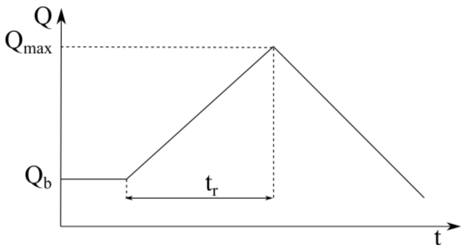

Fig. 1 Definition sketch of terms used to characterize experiments.

Two sets of unsteady flow, denoted by Hyd1 and Hyd2, were generated, both in the form of triangular hydrographs. They were generated by manual stepwise changing of valve opening. Each experimental flow is characterized by the base flow, Q_b, peak flow, Q_{max}, base water depth, h_b, peak water depth, h_{max}, and duration of rising limb, t_r. Definitions of terms used to describe flow characteristics are presented in Fig. 1. Unsteadiness degree of hydrographs is expressed by dQ/dt denoted by α_r and α_f along rising and falling limb, respectively. Additionally, unsteadiness parameter introduced by (Bombar et al., 2011) is evaluated:

$$P_{gt} = \frac{\left| gI - \frac{U_{max} - U_b}{t_r} \right|}{g} \qquad (1)$$

where g – gravitational acceleration [m s^{-2}], I – the bed slope [-], U_{max} – the peak mean velocity [m s^{-1}], U_b – the base mean velocity [m s^{-1}]. Values of these paramenters for the experiments are listed in Table 1. There is evident difference in Q_{max}, h_{max}, and α between the sets of unsteady flow. In both cases, the flow is subcritical with Froude number, Fr, approaching critical value for the maximum flow rate.

The channel bed was composed of gravel of mean grain size 4.93 mm. The bed was scraped flat before the experiments. During the experiments sediment was supplied manually from upstream. The following measurements were carried out: the flow rate, Q, in delivery pipe by ultrasonic flow meter; the water level, H, in 5 profiles along the flume x = 2.6 m, x = 3.6 m, x = 4.6 m, x = 5.6 m, x = 6.6 m by resistive sensors; the cumulative mass of sediment, M, was measured continuously in the outlet of the flume with a frequency of 1 Hz. Temporal and spatial variability of H is presented in Fig. 2 and cumulative mass measurements along with flow rate measurements in Fig. 3.

Evaluation of bed load rate

Bed load transport expressed as the weight of sediment transported per unit time, q, has been evaluated from measured cumulative mass $M(t)$ as its first derivative. Measurement data were noisy, and smoothing or filtering of results was necessary. In this study, Savitzky-Golay filter implemented in Matlab has been used to evaluate and filter q. Moving window of 41 elements has been applied to smooth data by a quadratic polynomial. As was shown in (Mrokowska et al., 2016), this filter gives results comparable to approximation of q by difference quotient followed by filtering by Fourier Transform method, very popular in filtering unsteady flow data (Bagherimiyab and Lemmin, 2013; Rowiński, 1998; Song and Graf, 1996). However, straightforward application of Savitzky-Golay filter makes this method more convenient in this case.

Evaluation of water slope and bed shear stress

Water slope, S_w, is a significant variable to characterize water flow. It is input variable to evaluate flow resistance, e.g., friction velocity, u_*, or bed shear stress, τ_b, from relation derived from flow equations (Mrokowska et al., 2015a,b):

$$u_* = \sqrt{\frac{\tau_b}{\rho}} = \left[gh\left(S_w + \frac{U}{gh}\eta + \frac{U^2}{gh}\vartheta - \frac{1}{g}\zeta \right) \right]^{1/2} \qquad (2)$$

where $\eta = \partial h/\partial t$, $\vartheta = \partial h/\partial x$, and $\zeta = \partial U/\partial t$. In particular cases, acceleration terms are small enough to neglect them, and Eq. 2 takes the following form:

$$u_* = \left(ghS_w \right)^{1/2}. \qquad (3)$$

Table 1. Characteristics of experiments.

Parameter	Hyd1	Hyd2
Q_{max} [m^{3}s^{-1}]	0.0435	0.0430
Q_b [m^{3}s^{-1}]	0.0021	0.0035
h_{max} [m]	0.102	0.103
h_b [m]	0.019	0.024
t_r [s]	411	256
Fr$_{max}$	0.94	0.89
Fr$_b$	0.58	0.56
α_r	0.00010	0.00016
α_f	-0.00010	-0.00016
P_{gt}	0.0081	0.0081

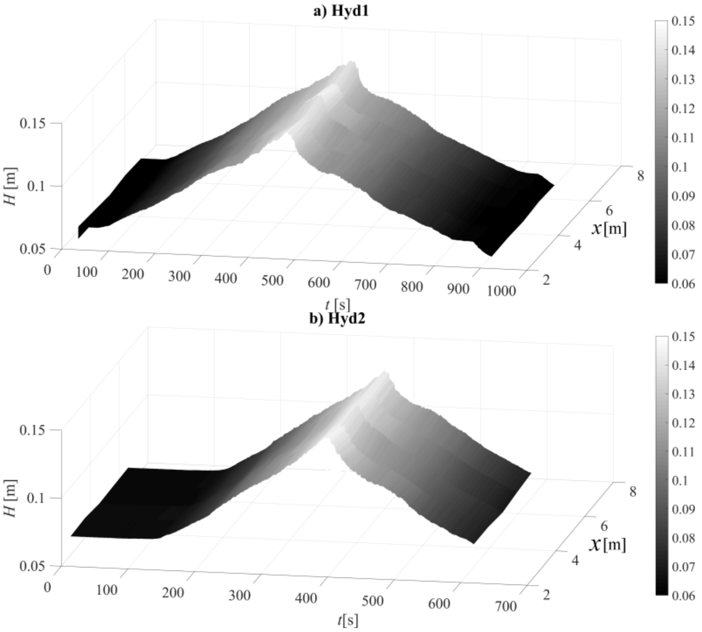

Fig. 2 Variation of water level in time and space.

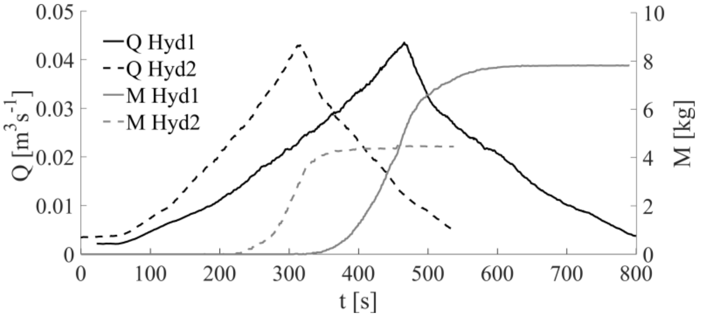

Fig. 3 Temporal variation of flow rate and cumulative mass transport – experimental data.

To evaluate S_w, spatial measurements of water level have to be taken in several locations along the channel. Then, S_w may be evaluated as a difference quotient (Mrokowska et al., 2015a). In this study, five point difference quotient, Eq. 4, and central difference quotient, Eq. 5, have been applied.

$$S_w \approx \frac{-H(x+2\Delta x) + 8H(x+\Delta x) - 8H(x-\Delta x) + H(x-2\Delta x)}{12\Delta x} \qquad (4)$$

$$S_w \approx \frac{H(x+\Delta x)-H(x-\Delta x)}{2\Delta x} \tag{5}$$

where Δx – the spatial step [m]. Water surface slope results require further filtering. In this study Fourier Transform has been applied. Results of bed shear stress have been corrected for side-wall effects by the procedure proposed by (Guo, 2015).

RESULTS AND DISCUSSION

Bed load rate and flow rate

Figure. 4 presents the temporal variability of bed load rate, *q*, and flow rate, *Q*. Time scales for flow and sediment transport are: Hyd1: 740 s for *Q*; 340 s for *q*, Hyd2: 470 s for *Q*, 220 s for *q*. As could be seen from the figure, there is a time lag between the peak values of variables – the maximum bed load rate occurs before the peak flow rate. Bombar et al. (2011) showed that the time lag is directly correlated with the unsteadiness of the hydrograph evaluated from Eq. 1. In this study, a time lag is 8s for Hyd1 and 9s for Hyd2. It is consistent with results of Bombar et al. (2011), as both hydrographs have the same value of P_{gt} (Table 1).

The relation between bed load rate and flow rate is in the form of a clockwise hysteresis (Fig. 5). It is characteristic of unarmored bed, when sediment is free to move from the beginning of flood wave (Humphries et al., 2012; Mao, 2012). In the case of Hyd2, *q*(*Q*) relationship perfectly follows a clockwise hysteresis. In the case of Hyd1, for $Q > 0.03$ m^3 s^{-1} bed load transport is more intensive along the falling limb than along the rising one, and hysteresis is not perfectly clockwise.

Water surface slope

Water surface slope results are critical for evaluation of bed shear stress from Eq. 3. For this reason, results of water surface slope are presented and discussed. As has been mentioned before, when measurements of water level are taken in several cross-sections, the water slope may be approximated by difference quotients. In this study, there were five measurement sections and water slope has been evaluated in the central one. Results of Eq. 4 and Eq. 5 followed by filtering by Fourier Transform for different configurations of sections have been compared in Fig. 6. S_{w1} has been evaluated from five point quotient, Eq. 4, for $\Delta x = 1$ m; S_{w2} – evaluated from central quotient, Eq. 5, for $\Delta x = 2$ m; S_{w3} – evaluated from central quotient, Eq. 5, for $\Delta x = 1$ m. For S_{w1} and S_{w2} , there are additionally shown results without filtering. It is apparent that the results are much more noisy for five point quotient. S_{w2} proved to be the most reliable evaluation, and it is in line with the observed negligible spatial variability of water level in the channel (less than 1 cm). Results of S_{w2} are close to bed slope *I*, as expected.

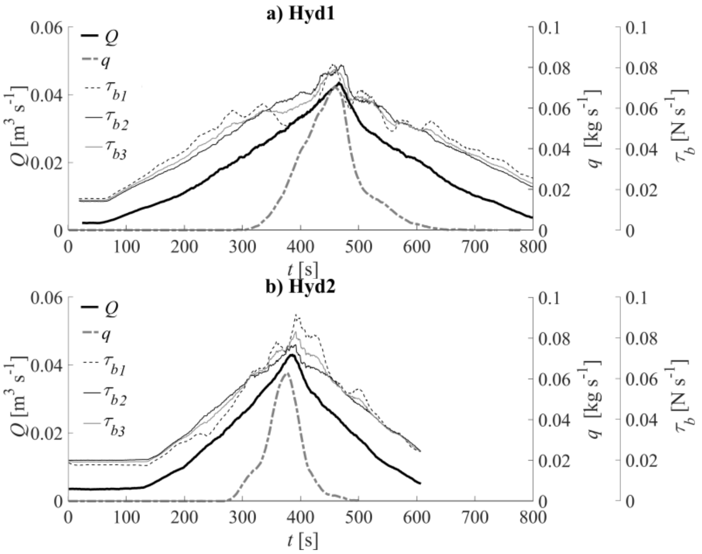

Fig. 4 Time evolution of bed load rate, flow rate, and bed shear stress.

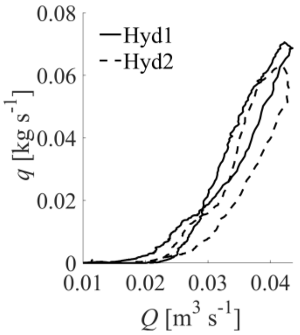

Fig. 5 Relation between bed load rate and flow rate for experimental data.

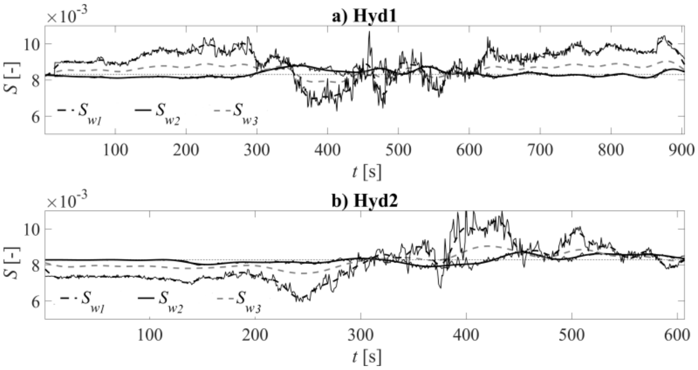

Fig. 6 Temporal variation of water surface slope.

Despite the fact that temporal and spatial variation of water level (Fig. 2) seems to be satisfactory, minor spatial fluctuations of water level make water slope S_{w1} to vary in unexpected way (Fig. 6), because water surface slope results are sensitive to the fluctuations of measurement data. In mobile bed conditions, such local fluctuations are more probable than in experiments with fixed bed, especially when the flow is shallow; in this experiment, the maximum water depth was about 10 cm (Table 1). Moreover, water surface slope is difficult to be controlled in laboratory channels, which has been pointed in (Qu, 2002). The effect of water slope may be mitigated in longer channels. Bombar (2016) published measurement data on water depth along rising limb in 18 m-long channel. In this respect, a question arises what dimensions of a channel can be treated as minimum to obtain unsteady flow undisturbed by boundary conditions.

Figure. 4 presents bed shear stress results, τ_b, obtained from Eq. 3 where water slope, S_w, has been evaluated in three presented ways denoted by subscripts 1, 2, and 3. It is apparent from the figure that all three bed shear stress sets follow the same pattern; hence, tested difference quotients do not affect bed shear stress results in this respect. However, it is not recommended to analyze the relation between the peaks of bed shear stress and bed load transport, especially when time lags are small and estimated time instant when the maximum value occurs may be due to the uncertainty of results. As each method of bed shear stress evaluation is uncertain to some extent, comparison of a few methods may be advantageous to interpret the results as shown in (Bombar, 2016; Qu, 2002).

CONCLUSIONS

Studies on bed load transport in unsteady flow have been carried out for a few decades but only recent years have brought increased interest in this topic. Laboratories all over the world try to uniform some procedures and experimental protocols to obtain compatible results. However, there is still a number of problematic issues that need to be solved. Some of them have been presented in this paper: controlling water surface slope during experiments, data filtering, interpretation of time lags between peak values. Other problems related to experimental design are: sediment supply methods (feed or no feed experiment, recirculation of sediment), sediment type and grain size distribution, the shape of hydrograph and the rate of unsteadiness. All these aspects should be considered in the light of the aim of research which is to discover the laws that govern sediment transport in nature. This cannot be achieved without applying scaling laws. Some effort in this respect have been already done, e.g., in (Cooper and Tait, 2009; Parker et al., 2003; Wang et al., 2015)

In our opinion, the future experimental studies have to develop more rigorous physical modeling procedures and scaling laws to take into account how experimental settings correspond to natural conditions.
Comprehensive analysis of all experimental sets from presented experiments will be provided in a separate paper.

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