A laboratory investigation of bed-load transport of gravel sediments under dam break flow

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Abstract

Dam break flows and resulting river bed erosion can have disastrous impacts on human safety, infrastructure, and environmental quality. However, there is a lack of research on the mobility of non-uniform sediment mixtures resulting from dam break flows and how these differ from uniform sized sediment. In this paper, laboratory flume experiments revealed that coarse and fine fractions in non-uniform sediment had a higher and a lower bed-load parameter, respectively, than uniform sediments of the same size. Thus, the finer fractions were more stable and the coarser fractions more erodible in a non-uniform bed compared to a uniform-grained bed. These differences can be explained by the hiding and protrusion of these fractions, respectively. By investigating changes in mobility of the mixed-size fractions with reservoir water levels, the results revealed that at low water levels, when the coarser fractions were only just mobile, the bed-load parameter of the finer fractions was higher than the coarser fractions. The opposite was observed at a higher water level, when a significant proportion of the coarsest fractions were mobilized. The higher protrusion of these grains had an important effect on their mobility relative to the finer grains. The transported sediment on these mixed-sized beds was coarser than the initial bed sediment, and became coarser with an increase in reservoir water level.

Key words: dam break, bed-load transport, gravel, laboratory flume

Introduction

Dams have been constructed all over the world to provide water supply for drinking, agriculture, industry, and power generation; they are also a key component of flood defense. However, when they collapse, the resulting floods can have disastrous impacts on infrastructure, human safety, and environmental quality. Dam breaks can take place due to overtopping, piping, slope instability, insufficient spillway capacity and earthquakes (Molu 1995; Bozkus 2004). Future changes in climate, particularly in terms of storm severity, are likely to increase the risk of dam failure as the majority of existing structures were designed based on past and current hydro-climatological conditions (Soares-Frazão et al. 2012).

Damage to infrastructure from sediment erosion and deposition can be as severe as the impact of the flood wave itself (Spinewine & Zech, 2007). The intensity of sediment transport close to the dam can be such that the rate of sediment transport is similar to the rate of water transport resulting in a mixed water-sediment flow (e.g. Outland 1963; Capart, 2000; Zech et al., 2009; Goutiere et al., 2011). Further away from the dam, significant morphological changes to the catchment can occur and in extreme cases, the morphology of the river and its surroundings can be completely reshaped.

Thus to fully understand the consequences of dam break, measurements or numerical models of sediment transport rate must be considered along with dam break flow velocity. Field observations are rare as they can be difficult, costly and dangerous to perform. Without field observations, however, validating numerical models for real-world dam failures is problematic. Thus, laboratory experiments, due to their relative simplicity, ease of control, and ability to generate repeatable datasets (Howard 2008), play an important role in the development and validation of these models. Over the last few decades, an abundance of laboratory experiments on dam break flows over fixed beds have investigated velocity distributions, flood propagation and water levels (e.g. Soares-Frazão & Zech 2002; Soares-Frazão 2007; Soares-Frazão & Zech 2008). Increasingly, the focus has turned towards experimental testing of mobile beds which better reflect conditions found in natural rivers (e.g. Fraccarollo & Capart 2002; Leal et al. 2002; Leal 2005; Spinewine & Zech 2007; McMulli, 2015). For example, Leal et al. (2002) investigated dam break over uniform mobile sand beds in a flume and showed that bed sediment mobility, initial downstream water depth and initial bed step height play important roles in the behavior of sediments dislodged downstream of a dam. Soares-Frazão et al. (2012) conducted similar experiments revealing that intense scour occurred near the failed dam and sediment deposition was present further downstream. Qian et al. (2017) conducted a laboratory investigation into the impact of partial dam break floods on bed topography and revealed that the scour and deposition patterns observed in previous studies over uniform beds also occur over non-uniform beds. The final bed surfaces showed a general coarsening trend in the intense scour and deposition areas. In other parts of the reach, small bed-forms, that produced a coarse-fine-coarse bed structure, were only observed in cases with non-uniform sediment.

Previous studies have only investigated the difference in temporal flow distributions and bed evolution between uniform and non-uniform beds. To the best knowledge of the authors, no other study has examined the effect of grain size uniformity on bed-load transport rates. This study is a first attempt to fill this gap by experimentally investigating the impact of dam break flows on bed-load transport rates over uniform and non-uniform sediments, with varying reservoir water levels and downstream bed slopes.

Methodology

Flume set-up

The experiments were carried out using a 12 m long by 0.5 m wide flume with a depth of 0.5 m. The dam break was simulated using a fast vertical PVC lift-gate that was installed 4.4 m from the upstream end of the flume (Fig. 1 and Fig A1 in the Appendix). The first 3.4 m of the flume was composed of fixed bed material and a 1 m long section immediately upstream of the gate was constructed of mobile sediment. Downstream of the gate, a 5 m long mobile section was created and two bed-load traps (each 0.15 m wide by 0.5 m long) were embedded at the end of this section. The remaining 2.3 m of the flume was constructed of fixed bed material. The thickness of the sediment sections was 6-8 d_{50} and the total volume of the reservoir was between 0.24 to 0.77 m^3, where d_{50} is the median bed sediment diameter. Ultrasonic sensors, operating at 25 Hz, measured water depth behind the gate at 4.30 m (Sensor 1) and downstream of the gate at distances of 4.90 m (Sensor 2) and 5.90 m (Sensor 3). Three digital cameras were installed: one at the gate location to calculate the opening time of the gate, a second at the end of the movable bed to record the arrival time of the flood wave, and a third camera at the two bed-load traps to measure the time taken for the traps to be filled. The opening times of the gate (from 0.15 to 0.25 s) reveal that the simulated dam breaks can be considered to have occurred instantaneously (Lauber & Hager 1998).

Experimental procedure

Four uniform gravel mixtures with mean diameters of 5.17, 10.35, 14.0 and 20.7 mm were investigated, as well as a non-uniform mixture with d_{50} of 12.5 mm and sorting coefficient (σ_g) of 1.7 that was composed of these four uniform sediments in equal weight proportions (Table 1). Each experiment was performed using a static reservoir water level (h_1) of either 0.15, 0.20 or 0.35 m upstream of the gate. A water depth of 0.01 m (h_0) was allowed to form downstream of the gate and was kept uniform for all experiments through the use of a downstream weir. Before beginning the experiments, the water level behind and downstream of the dam was set using ultrasonic sensors and point gauges. No sediment feed was used due to the very short duration of each experiment (between 8 to 25 s). To investigate the impact of bed slope on bed-load transport, a total of eight longitudinal slopes (S), ranging from 0.005 to 0.035, were used (Table 2). A photo of the flume (Fig. A1), an example of a hydrograph (Fig. A2) and changes in the sediment bed resulting from a dam break (Fig. A3) are presented in the Appendix. The flow unsteadiness was high due to rapid changes in the hydrograph. Thus there is uncertainty in the estimate of bed shear velocity (Mrokowska, & Rowinski, 2019). Sources of uncertainty include the movement of bed sediment affecting fluid momentum (Carbonneau & Bergeron, 2000) and a high level of ambiguity in defining the datum and bed shear velocity in a mobile bed (Nikora et al., 2007; Ferreira et al., 2012).

Dimensionless bed-load parameter

After each run, the transported sediment collected in the bed-load traps was dried, sieved and weighed fractionally. Using these samples, the bed-load transport rate was calculated and used to estimate the dimensionless bed-load parameter for the uniform (q_s^*) and non-uniform mixtures (q_{si}^*) [-]:

$$q_s^* = \frac{q_s}{\rho_s\sqrt{(s-1)gd^3}}, q_{si}^* = \frac{q_{si}}{f_i\rho_s\sqrt{(s-1)gd_i{}^3}} \quad (1)$$

where q_s is the bed-load transport rate of the uniform sediment [kg m^{-1}s^{-1}], q_{si} is the fractional sediment transport rate [kg m^{-1}s^{-1}], d is the mean size of the uniform sediment [m], d_i is the mean of the grain size fraction i [m], f_i is the proportion of fraction i in the bed surface [-], g is gravitational acceleration [m s^{-2}], ρ_s is the sediment density [kg m^{-3}], $s = \rho_s / \rho_w$ is the relative density of sediment [-] and ρ_w is water density [kg m^{-3}].

Impact factor

To assess the difference in the mobility of a non-uniform grain size fraction with its equivalent in a uniform sediment, the impact factor F_i was estimated (Li et al., 2016):

$$F_i = \left(\frac{q_{si}}{f_i}\right) / \left(\frac{q_s}{f}\right) \quad (2)$$

where f is the proportion of the uniform sized sediment in the bed surface [-] and thus is equal to 1. The finer fractions in a non-uniform mixture may be hidden by the coarser fractions, and thus, have an impact factor of less than 1. The converse is likely to be the case for the coarser fractions and thus they would have an impact factor greater than 1. If the mobility of a fraction in a non-uniform mixture is equal to the mobility of a uniform-sized counterpart, the impact factor is equal to unity.

Result and discussion

Difference in bed-load transport of uniform and non-uniform sediment

At a slope of 0.01, there was no transport of non-uniform sediment; however, there was active transport of uniform bed sediments of 5.17, 10.35 and 14.0 mm. This result implies that non-uniform bed material was more stable than the fine uniform bed sediments because of the presence of a 20.7 mm fraction. A comparison between the 14.0 mm fraction in the non-uniform sediment and its uniform sediment counterpart shows that the uniform sediment had a higher dimensionless bed-load parameter than the non-uniform sediment (Fig. 2a). At reservoir water levels of 0.12, 0.20 and 0.35 m with a slope of 0.02, the bed-load parameter for 14.0 mm uniform sediments was 71 %, 35 % and 27 % higher than for the counterpart non-uniform fraction, respectively. For the coarser fraction of 20.7 mm, the relation was reversed; at a slope of 0.03 the bed-load parameter was 26 %, 38 % and 17 % higher for the 20.7 mm non-uniform fraction than for the counterpart uniform sediment, respectively (Fig. 2b). This result is attributed to protrusion and hiding effects that exist in non-uniform sediments which enhance the mobility of coarser fractions and decrease the mobility of finer fractions. These effects are confirmed by the transported sediment being coarser than the initial sediment in the flume (Fig. 3).

To further highlight the impact of the finer fractions of the non-uniform sediments on the mobility of the coarser fractions, the fractional transport rate of the 14.0 mm (F14) and 20.7 mm (F20.7) fractions were compared to the rate of their uniform counterparts (Fig. 4). The results reveal that the 20.7 mm fraction was more mobile, while the 14.0 mm fraction was less mobile. This finding implies that the finer fractions in the non-uniform sediment caused the coarser fractions to be more easily eroded. Furthermore, the 14.0 mm fraction was less susceptible to erosion. These results are in accordance with those for steady (Li et al., 2016) and gradually varied flow conditions (Li et al., 2018). Figure 4 also shows that when the reservoir water level increased, the relative fractional rates tended towards one. Only at lower water levels and lower levels of hydraulic energy did protrusion and hiding effects become apparent. This result is also in accordance to previous findings for uniform flow conditions (Li et al., 2016).

Effect of reservoir water level on bed-load transport of non-uniform sediment

The change in the bed-load parameter of the non-uniform fractions with reservoir water level is shown in Figure 5 for three bed slopes. This figure shows that, for water levels of 0.12 and 0.20 m, the bed-load parameter of the finer fractions (5.17 and 10.35 mm) was higher than the coarser fractions (14.0 mm and 20.7 mm). The opposite trend was observed at a water level of 0.35 m. For example, with a slope of 0.02, the bed-load parameter for the finest fraction was 6.53 and 2.45 times higher than for the coarsest fraction at water levels of 0.12 and 0.20 m, respectively. For the water level of 0.35 m, at the same bed slope, the bed-load parameter for the coarsest fraction was 1.65 higher than for the finest fraction. These differences in mobility of the fine and coarse fractions with reservoir water level are likely to have occurred due to difference in shear stress. At the highest water level, there was sufficient force for the transportation of both coarse and fine fractions. Thus, the effect of enhanced protrusion of the coarse grains was apparent, causing the bed-load parameter for coarser fractions to be higher. In contrast, at the lower water levels, the shear stress was not high enough to transport sufficient proportions of coarse-grained sediment, thus the effects of enhanced protrusion on the mobility of the coarse grains was not observed. Thus overall, the effect of hiding and protrusion decreased with increasing water level. These changes in mobility with reservoir water level were reflected in the grain sizes of the transported sediments (Fig. 3); for slopes of 0.02 and 0.03, the median transported grain size increased with reservoir water level from 12.5 to 19.5 mm, and from 14.5 to 19.6 mm, respectively.

Future research should investigate further the effects of dam break flows on bed-load transport over a wider range of non-uniform sediment mixtures, with differing d_{50} and sorting, and over water-worked beds that better mimic the surface topographies of natural coarse-grained rivers (Cooper and Tait 2009). In addition, there is a need to examine whether the relative mobility of coarse and fine fractions differs between the rising and falling limb of a flood hydrograph (Wang et al. 2015), and if the flood hydrograph resulting from dam breaks acts to transport non-uniform mixtures in the same manner as unsteady flood hydrographs. Future studies should also focus on quantifying the bed topography adjustments due to dam break flows in order to provide detailed explanations for the changes in the mobility of non-uniform sediment fractions.

Conclusion

Laboratory experiments in a flume have quantified the mobility of non-uniform sized sediment in dam break flows and how this differs from uniform-sized sediment. The dimensionless bed-load parameter of the finer fractions of the non-uniform bed was lower than the same sized material on a uniform bed, although the coarsest fraction had a higher bed-load parameter. The finer fractions were more stable, and the coarser fractions were more erodible in graded bed sediment compared to a uniform-grained bed. By investigating changes in mobility of the mixed-size fractions with reservoir water levels, the results revealed that at low water levels, when the coarser fractions were only just mobile, the bed-load parameter of the finer fractions was higher than the coarser fractions. The opposite was observed at a higher water level when a significant proportion of the coarsest fractions were mobilized, and the higher protrusion of these grains had an important impact on their mobility relative to the finer grains. The transported sediment in these mixed sized beds was coarser than the initial bed sediment, and became coarser with an increase in reservoir water level.

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Table 1. Physical properties of bed sediments, where d_{50} is the median grain size of the mixture, σ_g is the sorting coefficient, d is the mean grain size, ρ_s is the sediment density and Φ is porosity

Sediment	**Fraction [mm]**	**d_{50} [mm]**	**σ_g [-]**	**d[mm]**	**ρ_s [kg/m^3]**	**Φ [-]**
Fine gravel	4.75-5.6	-	-	5.17	2391	0.4
Lower medium gravel	9.5-11.2	-	-	10.0.35	2375	0.4
Higher medium gravel	13-15	-	-	14	2900	0.45
Coarse gravel	19-22.4	-	-	20.7	2552	0.43
Graded (mixture)	4.75-22.4	12.5	1.7	13.57	2567	0.37

Table 2. Summary of the experimental conditions, where *d* is the mean grain size, *S* is the flume slope, h_1 is the reservoir water level, q_s is the bed-load transport rate and q_s^* is the dimensionless bed-load parameter.

d **[mm]**	***S*** **[-]**	**Run code**	h_1 **[m]**	q_s **[kg m^{-1} s^{-1}]**	q_s^***[-]**
5.17	0.005	A-1	0.12	0.07	0.02
		A-1	0.20	1.04	0.23
		A-1	0.35	1.14	0.34
	0.0075	A-2	0.12	0.57	0.17
		A-2	0.20	0.78	0.28
		A-2	0.35	1.16	0.37
	0.01	A-3	0.12	0.82	0.24
		A-3	0.20	1.10	0.33
		A-3	0.35	1.66	0.51
10.35	0.01	B-1	0.12	0.41	0.045
		B-1	0.35	3.62	0.39
14	0.01	C-1	0.12	0.29	0.014
		C-1	0.20	0.73	0.035
		C-1	0.35	1.12	0.055
	0.02	C-2	0.12	0.92	0.042
		C-2	0.20	1.09	0.053
		C-2	0.35	3.16	0.15
20.7	0.03	D-1	0.12	0.23	0.008
		D-1	0.20	0.88	0.03
		D-1	0.35	3.24	0.1
	0.0325	D-2	0.12	0.40	0.013
		D-2	0.20	0.95	0.033
		D-2	0.35	3.38	0.15
	0.035	D-3	0.12	0.51	0.017
		D-3	0.20	1.06	0.036
		D-3	0.35	4.83	0.17
Non-uniform	0.015	E-1	0.12	0.08	0.002
		E-1	0.20	0.42	0.017
		E-1	0.35	1.12	0.042
	0.02	E-2	0.12	0.14	0.01
		E-2	0.20	0.42	0.019
		E-2	0.35	1.61	0.058
	0.03	E-3	0.12	0.33	0.018
		E-3	0.20	1.13	0.058
		E-3	0.35	2.02	0.076

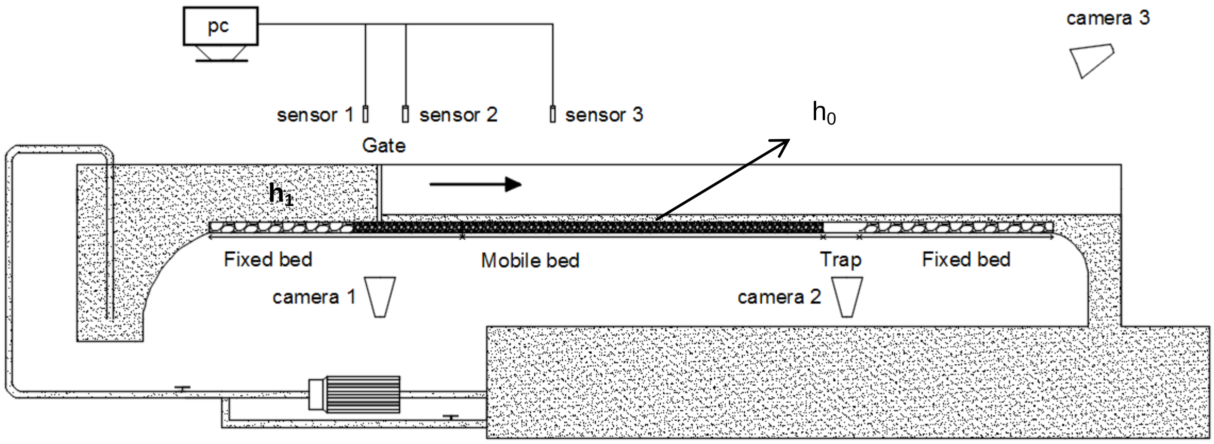

Fig. 1. Schematic of the flume (side view).

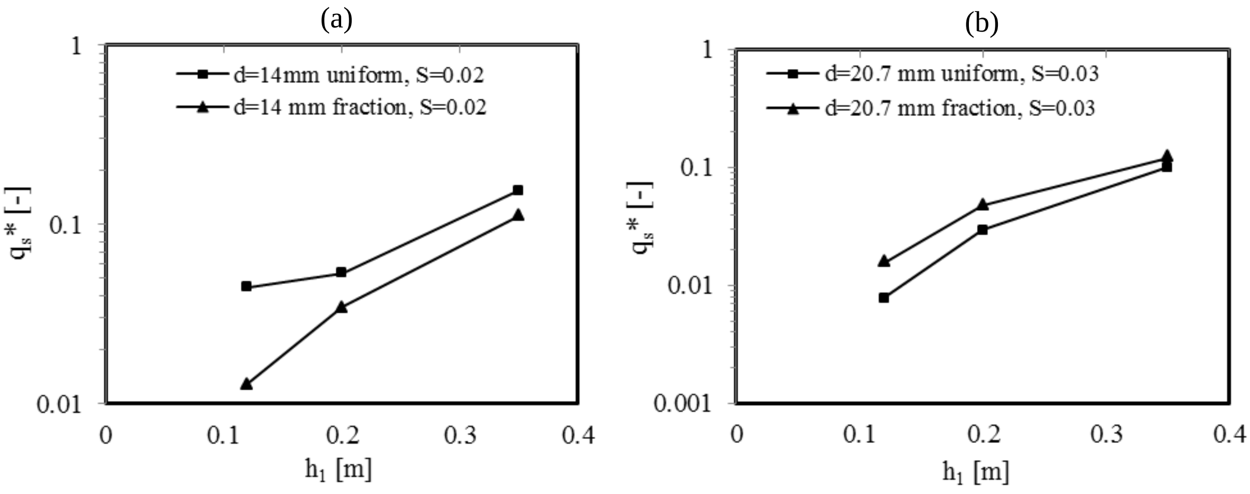

Fig. 2. Comparison of the dimensionless bed-load parameter (q_s^*) between the non-uniform fractions and uniform-sized counterparts at sizes of (a) 14 mm and (b) 20.7 mm.

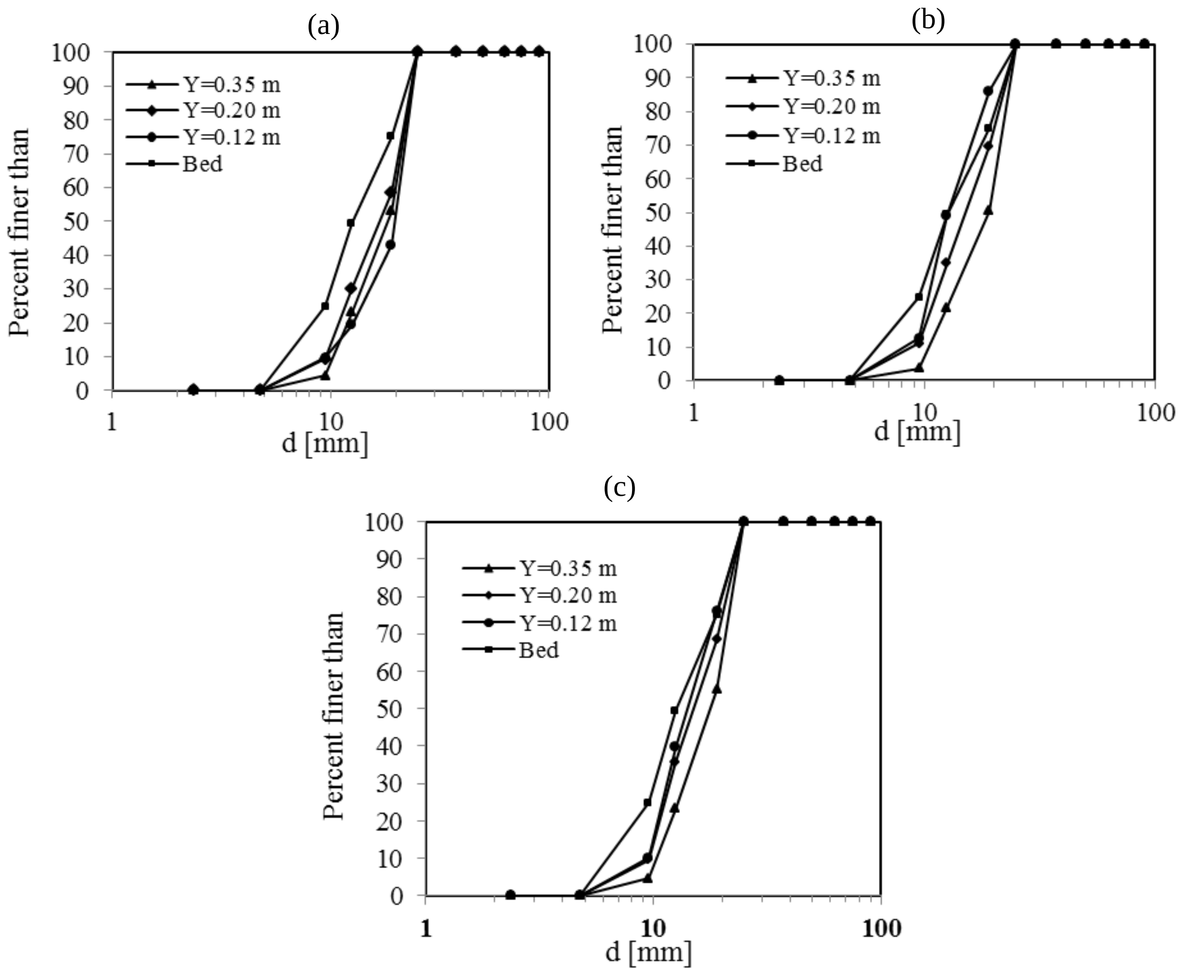

Fig. 3. Grain size distributions of the initial bed sediment and the transported non-uniform sediment at slopes of (a) 0.015, (b) 0.02, and (c) 0.03.

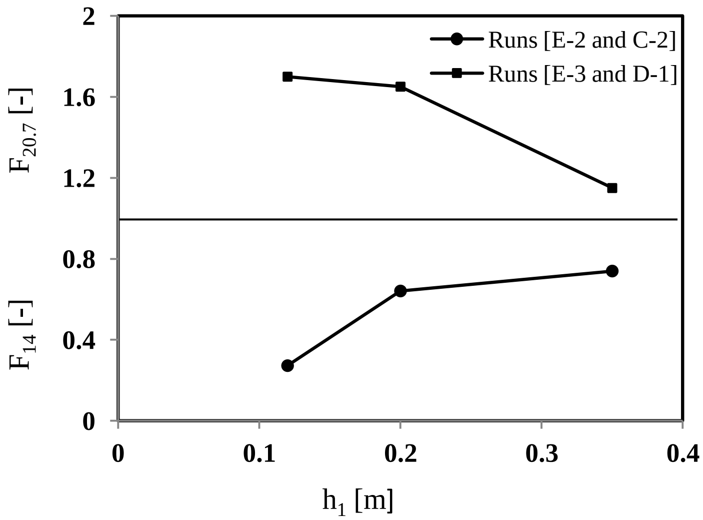

Fig. 4. Effect of reservoir water level (h_1) on the relative fractional sediment transport rate of two non-uniform fractions, 14.0 mm (F_{14}) and 20.7 mm ($F_{20.7}$) at slopes of 0.02 and 0.03.

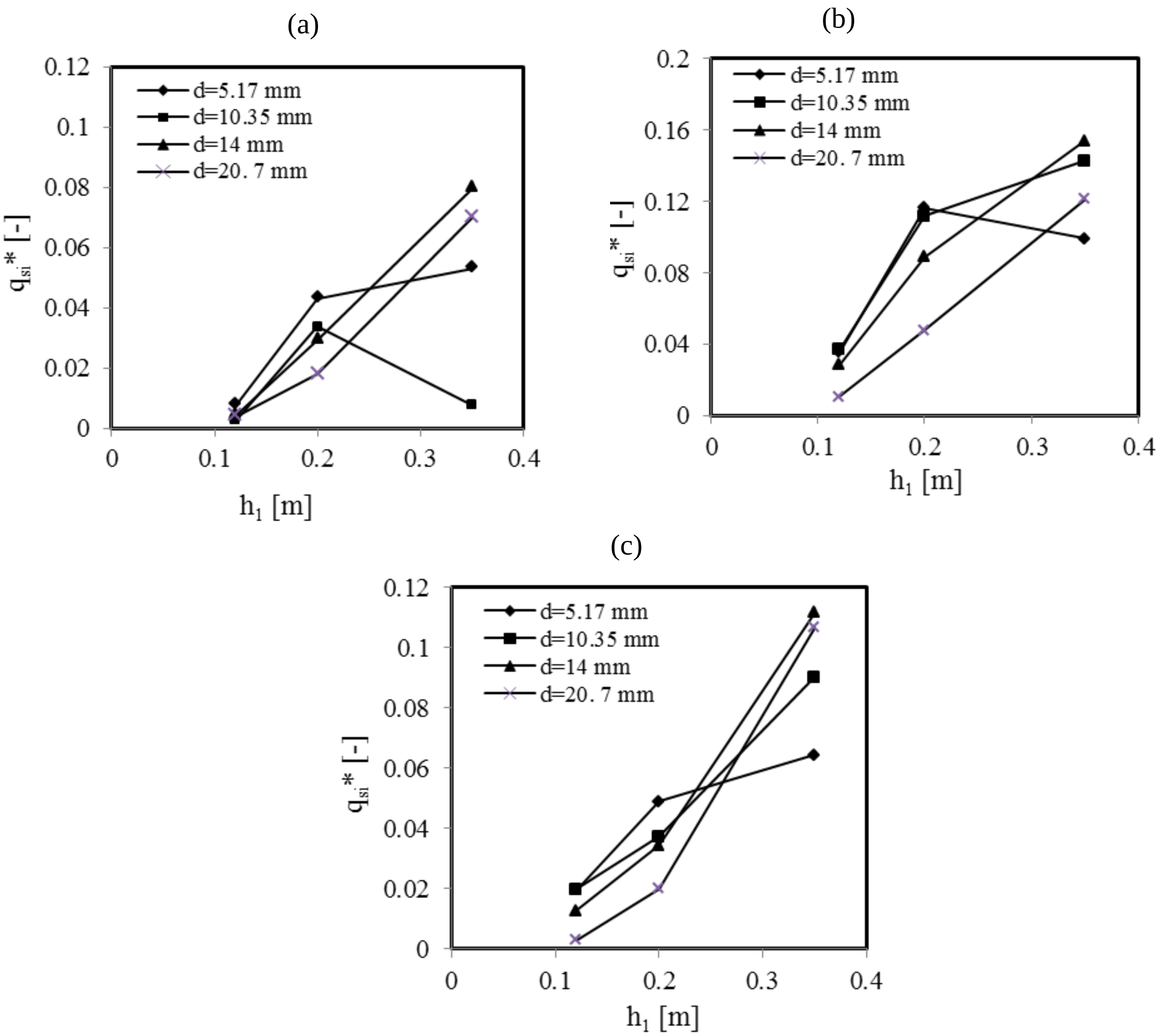

Fig. 5. Effect of reservoir water level (h_1) on the dimensionless bed-load parameter (q_{si}^{*}) at slopes of (a) 0.015, (b) 0.02 and (c) 0.03.

Appendix

Fig A. The location of the dam and its reservoir in the flume.

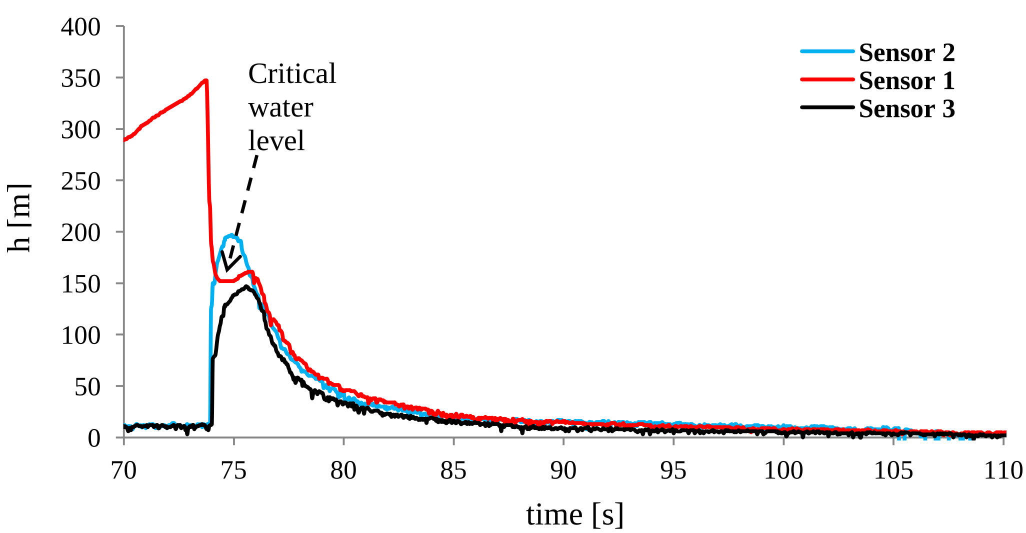

Fig. B. Discharged hydrograph resulting from dam break (red-line shows the water depth *h* in the reservoir, and the blue- and green-lines show the water depth at 0.5 m and 1.5 downstream of the dam.

Fig. C. Bed morphology changes after a dam-break flow