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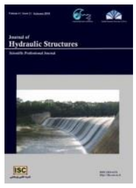

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Experimental investigation of bed evolution resulting from dam break

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Abstract

This study examines the relations between structures and shapes of streambed evolution after dam-break floods. A flume was used to simulate dam-break floods with variations of initial upstream water levels and variance, from uniform to graded, of bed sediments. Detailed measurements of the state and composition were made during these experiments. The data indicate that intense scour occurred immediately downstream of the "dam break" location in both uniform and graded sediments. The resulting bed surfaces of graded sediments showed coarse-fine-coarse structures in the areas with the lowest scour and highest deposition and various types of clusters (i.e., line and heap). This pattern was not observed in uniform-sediment beds. The scour holes changed from circular to oval-shaped in both uniform and graded sediments as bed slopes increased.

Keywords: Dam break, Experimental, Bed-surface composition, Graded and uniform sediment, Scour.

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1. Introduction

Dams, constructed all over the world to exploit water resources, to control floods, for flood defense, and to produce hydroelectric power, can fail. Failures might occur from natural processes, extreme natural events, human activities and processes, and engineering malfunctions. Dam failures often generate large death tolls and significant destruction of property and natural environments. For example, the failure of the Vajont Dam in Italy in 1963 caused 2,600 deaths, the 1993 failure of Gouhou Dam in China had 300 fatalities, and the failure of the Teton Dam in the United States in 1976 killed 11 and its economic damage exceeded $1 billion [1]. A statistical analysis of 534 dam failures from 43 countries before 1974 indicated that earth-rock dam failures accounted for the largest portion of all failures. Nearly half (49%) of failures were caused by overtopping, 28% by within-dam face seepage, and 29% by foundation seepage [1,2].

Analysis of sudden concrete dam failures is more important than concerns about earth-rock dams. Dam-break flooding is a hydraulic engineering and river dynamics issue that requires intensive study. Sediment transport rates near dams that fail are similar to the water transport rates, as outbursts produce flows of mixtures of water and sediment [3, 4]. Farther downstream of the dam, significant morphological changes occur and, in some cases, the morphology of the river and its surroundings are completely reshaped. In some cases, the loss of transported sediment exceeds the water fraction of flow. Investigation of the volumes and distribution of the sediments transported following dam breaks is critically needed.

Real-time field study following dam breaks is quite difficult and costly and suffers from uncertainties and low accuracy. Numerical modeling approaches (using Fluent, Open-Foam and other similar software) require an abundance of data, their operation can be difficult, and calibration is time-consuming. Most models were developed for fixed-bed conditions and consider neither the undoubtedly strong erosion potential of a transient flow nor related morphological changes in the channel bed [5]. Analytical solutions for sediment transport resulting from dam-break has been of limited value [6-7] because the interactions between flow, sediment, and changing bed morphology are usually ignored in models [5]. Recent developments have made it possible to include the consideration of the interactions between these parameters [8-12]. But these improvements have found limited study due to insufficient amounts of data and little information about highly transient sediments and flows [13]. Thus, physical modeling of sediment generation and transport is needed to fill this void. Physical modeling is similar to empirical field-based measurement in that they both require detailed empirical observation of actual events and processes [14]. Laboratory experiments are easier to control, however, and therefore provide potentially more robust and reliable data [13].

Researchers have conducted laboratory experiments around dam-break conditions in the context of fixed beds to investigate flood propagation, water levels, flow velocities, and the distribution of flows [15-21], but experiments that employ models of beds comprised of mobile sediments are closer to the "real-world" conditions of dam-break floods in natural rivers. Such floods tend to induce varying patterns of sediment transport and morphological changes in rivers. Capart and Young [3] made the first study in a fine sediment mobile bed in a small-scale narrow flume. Other similar experiments were carried out with different bed sediment compositions and different upstream and downstream water levels [22-24]. Goutiere et al. [4] constructed a channel to investigate dam-break flows and morphological changes in coarse, uniform, sand-sized bed material near an abruptly widening segment of the "stream." Only non-intrusive techniques were used to measure the model's water levels, bed levels, and surface velocity to avoid affecting the geomorphic processes in the experiment. This test revealed that severe scour occurred at the corners of the abrupt channel expansion. Soares-Frazão, and Zech

[17] simulated an abruptly widening channel to study the effect of dam-break flood propagation on morphological evolution of the bed near the widening cross-section. Soares Frazo et al. [12] conducted experiments of two-dimensional dam-break flows over a uniform bed of sand. They found that intense scour occurred near the failure site and sediment deposition occurred downstream. Wu et al. [25] investigated the effect of dam break flow on sediment transport rates using non-uniform rectangular mesh. They concluded that the model performed well for flow depth, velocity, and bed flux predictions. Issakhov and Yeldos Zhandaulet [26] investigated the effects of dam break flow on movable beds using the volume-of-fluid (VOF) method and concluded that their model was well balanced and reliable. Most research has focused on flow propagation generated by dam breaks. Rarely have experimental studies investigated the effect of dam breaks on bed morphology. Qian et al. [13] investigated the effects of dam-break flow on bed morphology in uniform sand (d=0.35 mm), gravel (d=3 mm), and mixed gravel and sand (d=2.5). The results showed a general coarsening of sediment in the areas of intense scour and deposition.

A few experimental studies were carried out with uniform bed sediments and some of these also used poorly sorted sediment (Qian et al. [13]), a condition that is not representative of natural rivers. The purpose of this study is to evaluate the impacts of dam-break flooding on the morphology of uniform beds of varying (but specific) sediment sizes and of beds of graded sediments with wider ranging sediments. These conditions are rarely reported in the literature. It is critical to determine how bed evolution in graded sediments is different from bed evolution in uniform sediments. In addition, the initial upstream water levels are also considered to be important factors.

2. Material and methods

2.1. Bed material properties

Four uniform gravel mixtures with mean diameters of 5.17, 10.35, 14 and 20.7 mm and specific gravities of 2.55, 2.90, 2.37 and 2.40 and a non-uniform mixture that was composed of these four uniform sediments in an equal-weight proportion were used in flume experiments. The median particle size of the mixture, specific gravity, uniformity coefficient, standard deviation and geometric standard deviation were determined (Table 1).

Table1 . Physical properties of bed sediments used in this study

Sediment	Fraction, mm	ds_{50}	σ_g	Mean size (d_m), mm	Density, kg/m^3	Porosity
Fine gravel	4.75-5.6	-	-	5.17	2391	0.4
Lower Medium Gravel	9.5-11.2	-	-	10.35	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

2.2. Flume set-up and experimental approaches

The experiments were placed in a 12 m long, 0.5 m wide, and 0.5 m deep flume with glass side walls. A dam break was simulated using a manually raised and lowered fast-vertical PVC lift-gate installed 4.4 m from the upstream end of the flume (Fig 1 and 2). A 1 m section immediately upstream of the gate was constructed of mobile sediment, and the remaining 3.4 m upstream was composed of fixed bed material. The mobile bed downstream of the dam was 5 m long and a bed-load trap, 30 cm wide and 50 cm long, was embedded at the end of this mobile section. The remaining 2.3 m at the downstream end of the flume was constructed of fixed bed material. The thickness of the sediment sections was 6-8 ds50 and the total volume of the reservoir was between 0.24 to 0.77 m3, depending on the water level used.

To investigate the impacts of bed slope on bed transport rates and finally bed evolution, a total of eight flume slopes, from 0.005 to 0.035 m m-1, were used; the number varied with the sediment diameter. Thirty-eight experiments were performed. Three ultrasonic sensors operating at 25 Hz were installed behind the gate – (at 4.30 m; Sensor 1) – to record the temporal evolution in reservoir water level, and after the gate – (at 4.90 m; Sensor 2 and 3) – to measure hydrograph near the failed dam. The celerity in dam break location varied between 1.4 m/s (for dm= 5.17 mm at a slope of 0.005 m m-1 and a water level of 0.12 m) to 4.7 m/s (for dm= 20.7 mm at a slope of 0.035 m m-1 and a water level of 0.35 m).

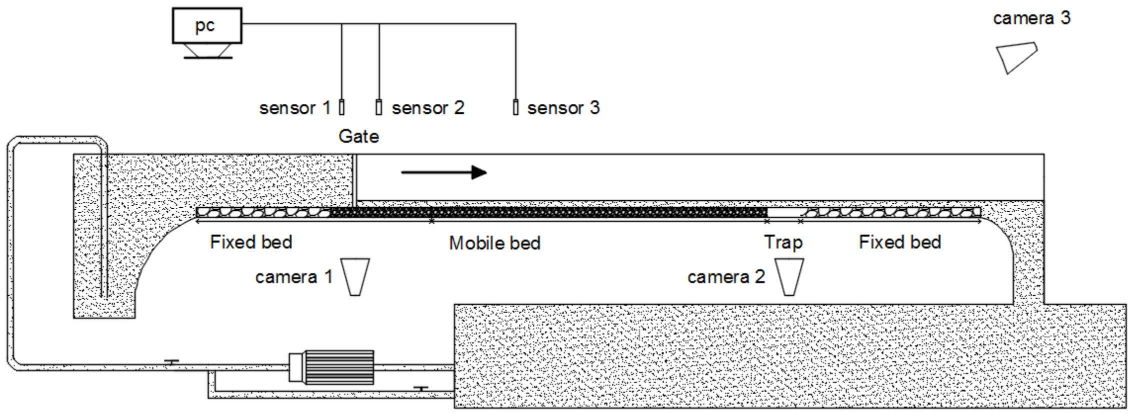

Figure 1. Schematic of the flume (side view).

Figure 2. The location of dam and its reservoir in the flume (Physically model set-up)

2.3. Experimental procedure

Each experiment was performed using some static water levels of 0.35, 0.20 and 0.12 m upstream of the gate and 0.1 m downstream of the gate. Before starting each run, the water level behind and downstream of the dam was set using the ultrasonic sensors and point gauges, respectively, and all the valves adding water to the reservoir were closed. The experiment began when the gate (i.e., the dam) was opened (i.e., a failure occurred) and ended when the water that had been stored behind the dam was completely discharged. Mean base-time of hydrographs are about 20 s. The main hydraulic parameters were recorded and tabulated (Table A in Appendix).

3. Results

After each experiment, the water in the flume was slowly drained. The surface of the movable section of the flume was photographed. Photographs of the uniform bed sediment of 5.17 mm diameters with a reservoir level of 35 cm and a bed slope of 0.01 m m-1 showed that intense scour occurred downstream of the failed dam and a series of scour holes were created; the greater the distance downstream of the failed dam, the smaller were the holes and less was the scour. Due to high slopes, water levels, celerity, and short erodible beds, there was virtually no deposition at the downstream end of the movable bed, something that had been observed in other studies (e.g., Qian et al., [13]). Very low deposition from reservoirs of 12 cm occurred, however. This may be due to insufficient mobile bed length to generate deposition at end of the movable bed. A short movable bed was used to trap transported sediment to calculate the bedload transportation rates. Longer movable beds, would generate deposition of the transported sediment before the sediment trap. It is noteworthy that between each intense scour hole, there were large deposits of sinusoidal shapes. This was also observed in Qian et al. [13].

Figure 3. Bed topography resulting from dam break for sediment of 5.17 mm, water level of 35 cm, and bed slope of 0.01.

When the bed material was comprised of 5.17 mm sediment, the bed slope was 0.01, and the water level was 35 cm, the failure caused intense scouring 2.9 m downstream. When the slopes were lower – 0.0075 and 0.005 – changes in the bed were negligible. When bed sediment was 10.35 mm, the water level in the reservoir was 35 cm, and the bed slope was 0.01, high scour occurred in the first 2 m. When reservoir depths were 20 cm and 12 cm, high scour occurred only 0.5 m downstream of the dam. These relationships were observed regardless of bed sediment grain size.

4. Discussion

Theoretically, the kinetic energy of dam-break flows depends upon the different water levels upstream and downstream of the dam. As these differences increase, sediment transport rates and bed deformations should similarly increase. When bed topography, bed materials, and water levels are held constant and only the slope of the bed changes, the shape of the scour hole will deform from circular to ovate. This may be the result of the changing angle of impact of upstream flow on bed sediments. The lower the bed-slope, the greater is the angle of impact and this causes the shape of scour-depth to be circular. The more the bed-slope increases, the lower is the angle of impact, generating ovate scour.

Sediment sorting in the scour and deposition areas of the graded bed sediment follows the rule that the locations of deepest scour and of highest deposition have the coarsest and finest sediments, respectively (Fig. 3). The greater the distance from the scour hole, the finer the bed sediment becomes. The greater the distance from the deposition area, the more coarse the bed sediment becomes.

The shapes of scour patterns and the scour holes are similar for uniform and non-uniform sediments near the dam. A hole created by scour and a hill formed by deposition are constructed in both conditions in the upstream end of the movable bed. But scour depth for graded sediment is larger than for coarse uniform sediment due to the involvement of fine sediment, but the depth is smaller than for fine bed sediment due to the involvement of coarse fractions. This was also observed in Qian et al. [13]. The differences were apparent in the downstream section of the stream bed: in graded bed sediments a narrow spiral scour was created downstream, a great distance from the failed dam. This was not observed in uniform bed sediments. It seems that this feature occurs because fine and coarse fractions respond differently to flow variations or selective sediment transport in the flood wave (Fig. 4b, yellow dash line). A second difference is a formation of clusters in graded sediments that are not observed in uniform sediments. In this study, the two most common clusters are line- and heap-constructed (Fig 4a, orange dash line).

Figure 4.a. Bed sediment composition in scour and deposition area

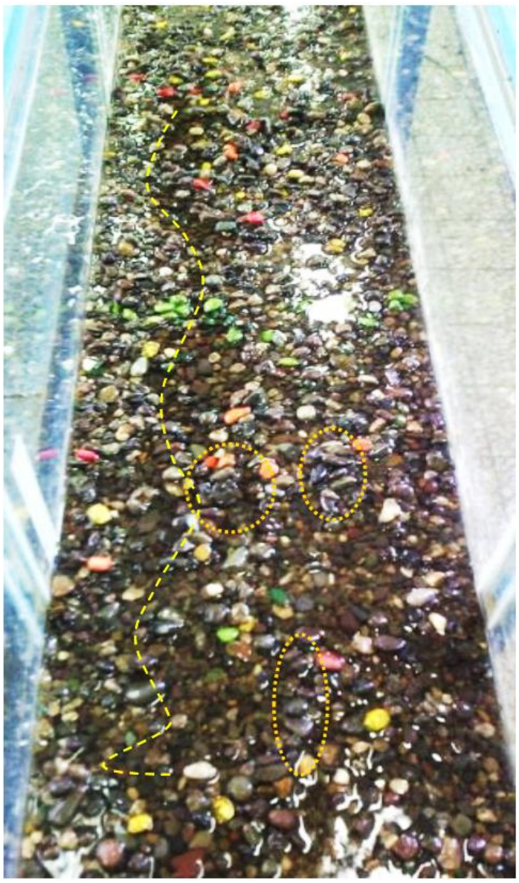

Figure 5.b. Downstream end of non-uniform movable bed sediment scour in a selective manner

These results of these experiments can be compared to similar studies of bed topography. Soares-Frazo et al. [12] investigated the impacts of dam-break floods on uniform bed sediments with a horizontal bed and they observed similar bed topography: near the failed dam, the scour was severe. They only examined uniform bed topography, however. Natural rivers have a wide spectrum of sediments (and are usually mixed sediments). Similarity, Leal et al. [19] and Leal [20] also examined the impact of differences between upstream and downstream water levels on flow patterns and bed topography. Qian et al. [13] investigated the impacts of variations of reservoir levels on bed topography in uniform sand, gravel, and blend grain-size sediments. They also evaluated the bed topography caused by bed sediment sorting after dam-beak floods. Our results are consistent with Qian et al. [13] in terms of bed topography: finer fractions cause non-uniform movable beds to become more erodible, scour holes toward the middle of the stream course become coarser, and the sediment at the location of highest deposition was finer. The differences in our observations are that we examined a wider assortment of bed material sediment size, examined both uniform and mixed sediments, and conducted the first comparison between the fractions and uniform counterparts in the context of a dam-break flood.

We recommend that future experiments vary the bed material composition with a wider range of sediment sizes and compare two or more beds composed with the same fractions but with different d50 (low and high d50). This may provide better insight into the impact of bed composition on sediment transport rates and bed topography. We also recommend that sediment size and distribution be measured. These were calculated after every run of the experiment by taking samples of bed material and by drawing the topography of the resulting stream beds with mobile laboratory laser scanners.

Physical experiments are largely constrained by the comparatively small spaces that can be realistically accommodated in laboratories, and thus they may not fully reveal the long-term mechanism of the flow. This can be considered to be the main source of uncertainty not only in this study, but is endemic to the experimental study of dam-breaks as a whole.

5. Conclusion

This study conducted a series of flume experiments to determine the impact of dam-break floods on bed topography with different bed slopes. The main results are:

1. The greater the difference between water levels above and below the dam, the more intense is bed scour in both uniform and graded bed sediments.
2. As bed slope increases, the shape of scour changes from circular to ovate.
3. The resulting bed sediment surface exhibited a coarse-fine-coarse structure and this pattern reflected the locations with the deepest scour, the highest deposition, and the deepest scour.
4. A narrow spiral scour scar is found at the downstream edge of the mobile bed in graded bed sediments, but not in uniform sediment.

The results of this study yields information to improve understanding of the similarities and contrasts of responses to variation in flow (including rapidly changing flow rates) and uniform and graded bed sediments. It more clearly depicts the effects of grain ize on bed sediment composition. And it provides new empirical data to test and validate mathematical models of dam-break floods to study bed topography and the composition of superficial sediments in the beds of streams after extreme floods.

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Appendix

Table A. Summary of experiment conditions

D, mm	Slope, m m^{-1}	Y, cm	q, kg m^{-1} s^{-1}	I, No S^{-1}	Running code
5.17	0.05	35	1.14	0.034	A-1
		20	1.04	0.022	A-1
		12	0.07	0.003	A-1
	0.0075	35	1.16	0.039	A-2
		20	0.76	0.028	A-2
		12	0.57	0.016	A-2
	0.01	35	1.66	0.06	A-3
		20	1.10	0.039	A-3
		12	0.82	0.021	A-3
10.35	0.01	35	3.62	0.054	B-1
		12	0.41	0.008	B-1
14	0.01	35	1.12	0.0137	C-1
		20	0.73	0.009	C-1
		12	0.29	0.005	C-1
	0.02	35	3.16	0.033	C-2
		20	1.09	0.01	C-2
		12	0.92	0.008	C_2
20.7	0.03	35	3.24	0.015	D-1
		20	0.88	0.006	D_1
		12	0.23	0.001	D-1
	0.0325	35	3.38	0.02	D-2
		20	0.95	0.007	D-2
		12	0.40	0.002	D-2
	0.035	35	4.83	0.031	D-3
		20	1.06	0.008	D-3
		12	0.51	0.003	D_3
Graded	0.015	35	1.12	0.029	E-1
		20	0.42	0.025	E-1
		12	0.08	0.011	E-1
	0.02	35	1.61	0.038	E-2
		20	0.42	0.029	E-2
		12	0.14	0.016	E-2
	0.03	35	2.02	0.052	E-3
		20	1.13	0.046	E-3
		12	0.33	0.027	E-3

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