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Experimental design of a diversion structure of granular debris flows

M. Studer, F. Hachem & J-L. Boillat
Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland.

ABSTRACT: Many alpine torrents convey regularly debris flows of high destructive hazard. After several granular events observed in Bruchji's torrent near the Blatten village in the Swiss Alps, it was decided to manage the risk of similar debris flows by designing and constructing a control structure inside the torrent bed. Associated with a breach in the right bank side of the torrent, this control structure should divert part of the moderate and high debris flow events toward the original alluvial cone. Two different configurations of the control structure were tested and optimized through a series of physical tests. The basic concept of this structure is to create a local lateral contraction of the torrent section topped by a horizontal rack or by a deflector beam. A physical model at the scale of 1:20 was built and granular debris flows were simulated by four successive discrete pulses. The behavior of the structure was tested inside the linear part and inside the bend of the channel reach. The geometry and dimensions of the control structure were also optimized to divert laterally a maximum volume of debris flow materials.This paper describes the physical model experiments, presents and discusses the main test results, and proposes an optimized geometry of the control structure. The most efficient configuration consists of a unilateral contract of the channel flow section inside a channel bend and to install a deflector beam.

Keywords: Granular debris flows, Experimental study, Diversion structure, Physical scaled modeling

1 INTRODUCTION

1.1 *Problematic*

The catchment area of Bruchji's torrent, a tributary of Kelchbach river in the Swiss Alps, has steep rock slopes covered with unconsolidated materials. During heavy precipitation events, large amount of liquefied landslides of saturated debris are regularly initiated and transported toward Blatten village located on the downstream end of the catchment area (Figure 1). Two historical events of granular debris flow have been observed in 1995 and 2001. The texture of these flows was composed of material ranging in size from clay to about 0.5 m^3 of rock boulders. The high flooding risk induced by the limited flow capacity of the Bruchji's reach that travels the Blatten village, has urge the local authority to search for suitable solutions to protect lives and goods. An interesting proposition to divert granular debris flows has been proposed [11]. The aim of this solution is the partial diversion of moderate and high debris flow events from the torrent's bed toward a managed area inside the historical alluvial cone. In this area, a progressive drainage and phase separation of the water-sediment mixture will occur. The solid part of the flow will settle down and water will be redirected back to the torrent's bed by means of dikes that bound the deposition area.

1.2 *Basic design guidelines*

The design report [11] suggests the following basic guidelines: (i) not more than 10000 m^3 of debris flow should reach the existing deposit reservoir, (ii) the excess volume of debris flow should be diverted to the future deposition area or forced to be stopped and settled down inside the torrent's bed along the reach situated upstream from the existing deposit reservoir, (iii) the volume of solid material deposited in the bed of the torrent should be kept as low as possible, and (iv) the control structure should provides a way for

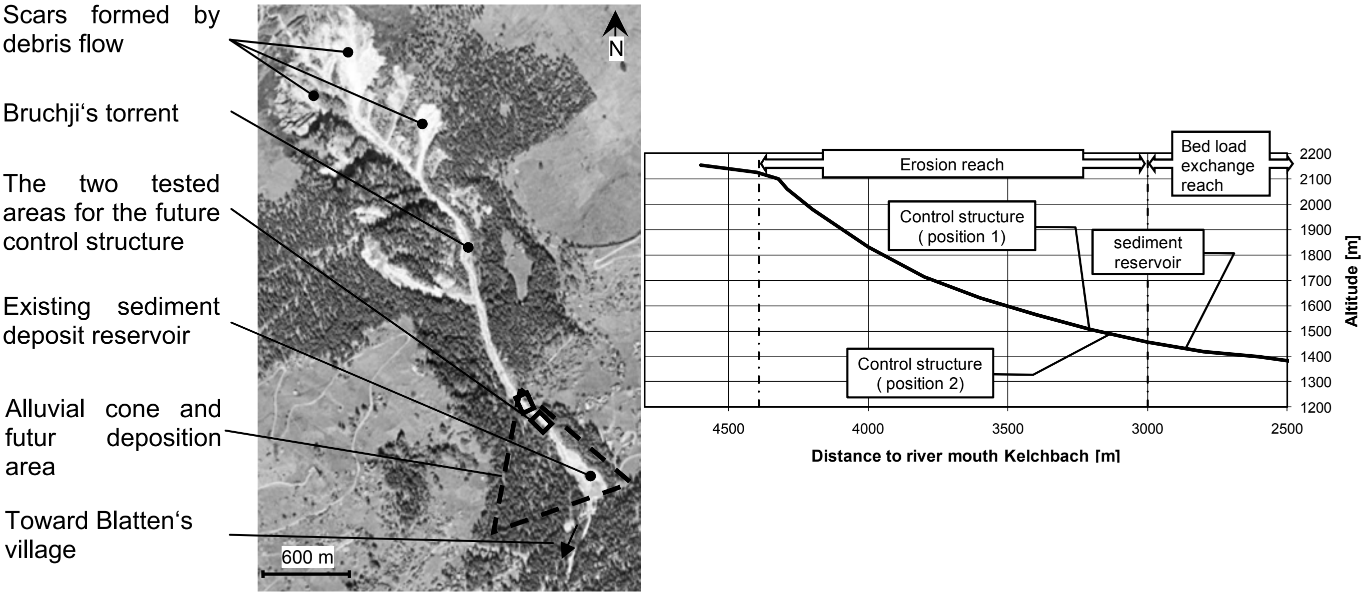


Figure 1. Arial view (left) and schematic longitudinal profile (right) of the Bruchji's torrent upstream from the Blatten village.

clear water following the debris flow events, to return back progressively to the torrent's bed.

The basic concept is to create a local lateral contraction of the torrent section and to open a breach in the right bank side of it. The local artificial narrowing and widening of the flow section leads to a partial energy dissipation of the flow. This induces local sediment deposition inside the bed which creates an obstacle to the following debris flow masses. When the depth of deposits reaches the crest level of the lateral breach, part of the debris flow is diverted toward the deposition area. The final constraint imposed to the control structure is that clear water flowing with classical bed load transport should not generate flow diversion through the breach.

1.3 *Aim of the paper*

The reliability of the suggested risk management solution depends on the efficiency and robustness of the future control structure. To enhance the behavior and optimize such a complicated structure, physical model tests for two different configurations A and B (Figure 2) and two different locations of the control structure (Figure 1) were carried out in the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). The physical model was designed to generate successive discrete surges of granular debris flow.

This paper presents the physical model set-up, describes some tests that have been carried out, and provides a rather detail analysis of results. It aims to determine the widths of the channel contraction and lateral breach, the level of the horizontal rack for the A type control structure, the lower level of the deflector for the B type, and the crest level of the diversion breach.

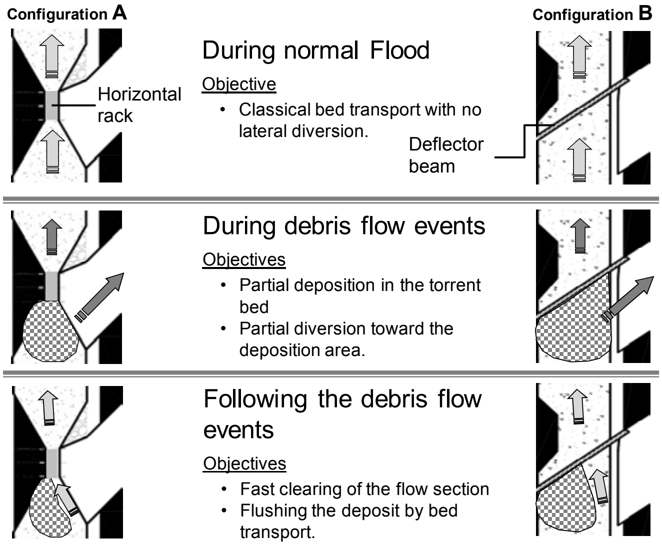


Figure 2. Schematic presentations of the operation process of the two tested configurations of the control structure with bilateral (left) and unilateral (right) contractions of the torrent cross-section.

2 EXPERIMENTAL SET-UP

2.1 *Prototype characteristics*

The investigated reach of Bruchji's torrent has a trapezoidal cross section with 13 m of base width and 45 degrees of banks slope. It is a quasi-prismatic reach with a constant longitudinal slope of 26 %.

Bruchji's floods are mainly caused by convective rainfall during thunderstorms. For flood return period of one hundred years, the water peak discharge lies roughly between 22 and 26 m^3/s [11]. The Probable Maximum Flood (PMF) is estimated to 40 m^3/s (Table 1). The one hundred years and the PMF flood events can mobilize large volumes of solid materials estimated between 30000 and 50000 m^3 for the former (rare events) and 70000 and 100000 m^3 for the latter (possible events) (Table 2). The existing sediment reservoir has a volume capacity of about 10000 m^3. Its capacity is sufficient for debris flow events generated by rainfall of 20 years return period. The maximum sediment volume of 100000 m^3 corresponds to the available materials that can be potentially mobilized during one single PMF event.

Table 1. Bruchji's water discharge during floods [11]

Flood return period	Discharge [m^3/s]
20	12 – 20
100	22 – 26
PMF	40

Table 2. Estimated volume of debris flow events [11]

Events	Return period	Volume [m^3]
Frequent	20	10000 – 15000
Rare	100	30000 – 50000
Possible	300	70000 – 100000

2.2 *Model characteristics*

The physical scaled model of the Bruchji's torrent was built respecting a geometrical scale of 1:20. The physical model covers a prototype area of 140 m long and 65 m wide (Figure 3). It includes also a small area of the future deposition reservoir at the right hand side of the torrent. A schematic 3-D view of the physical model of 7 m long and 3.25 m wide is shown in Figure 4.

At the upstream boundary of the model, a 0.5 m^3 tank is used to prepare the mixture of granular debris flow. This tank is equipped with a regulated gate with fast opening maneuver. The discharge of the debris flow is controlled by adjusting the height of the rectangular section defined laterally by the tank walls and vertically by the torrent bed and the lower edge of the gate.

The mean front velocity v, the front height h, and the flow rate Q_s of the upstream debris flow are determined by ultrasonic height measurements spread out over the entire length of the modeled reach.

Considering the depth of the unconsolidated and potentially movable materials that cover the Bruchji's catchment area, a prototype volume of one single surge of 4000 m^3 of debris flow has been considered. The design debris flow event was taken as being a "Frequent event" according to Table 2. Therefore, the performance of the control structure has been evaluated by simulating four consecutive and identical pulses with a total prototype volume of 16000 m^3.

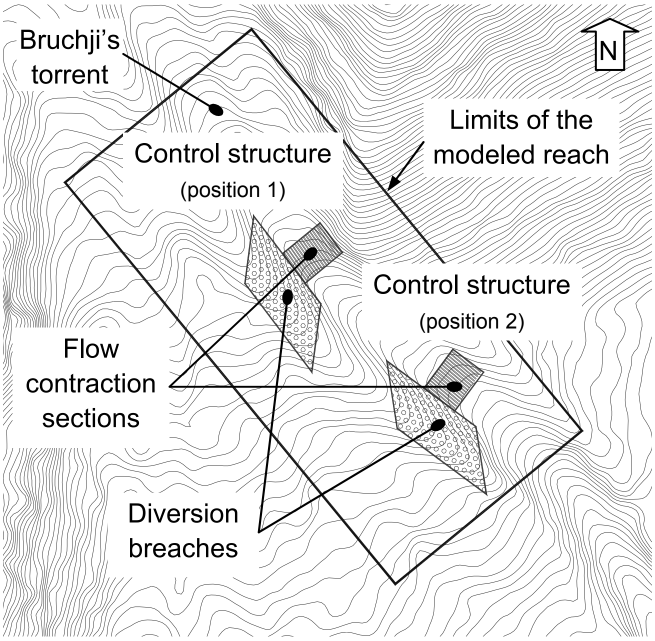


Figure 3. Topographical plan view of the modeled reach of the Bruchji's torrent with the two different positions of the control structure.

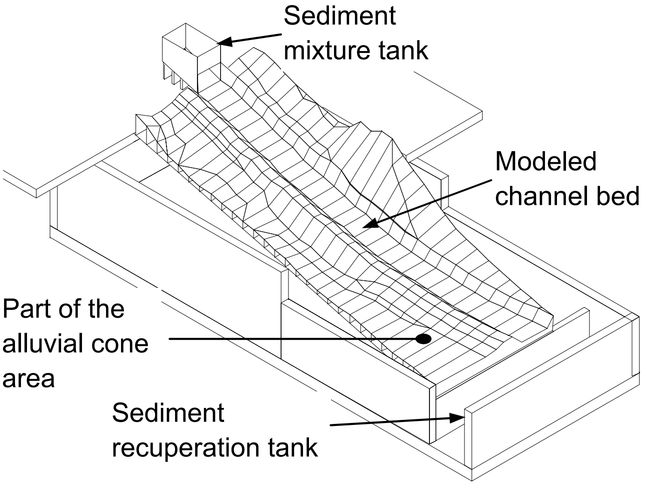


Figure 4. Topographical 3-D view of the scaled physical model.

Two different positions for the control structure were tested. The first one was at the end of the straight line of the channel while the second was at its curved part.

2.3 *Similarity criteria and grain size distribution*

The physical model was built according to Froude similarity which preserves the ratio of inertial to gravitational forces in model and prototype.

After a series of preliminary tests with clear water and debris flow without the control structure, the following three main parameters were adjusted: (i) the opening area under the mixture tank gate, (ii) the roughness of the channel reach, and (iii) the grain size distribution and water content of the debris flow mixture.

In clear water tests, the channel roughness was created using gravels of d_{90}= 1.5 cm which is in Froude similarity with the d_{90}= 30 cm of Bruchji's torrent measured during an in-situ line sampling campaign. Having no additional information on the prototype depth of flow during clear water floods of 20 years return period, it was decided to fix the crest level of the diversion breach and the horizontal rack grid for the A type control structure 1.4 m above the torrent bed (in prototype scale). It was the same level that reaches the water surface during tests without debris flow.

For debris flow tests, it was found that the channel roughness used in clear water tests drains the debris flow mixture during its descent. The flow decelerates and stops before reaching the downstream channel edge. Therefore, different channel roughnesses were tested by smoothing more and more the channel surface. The measured debris flow parameters h, v and Q_s for about 20 tests with the same channel roughness were very scattered. For a completely smooth channel, the mean vlues of h, v and Q_s were around 1.2 m, 5 m/s and 100 m^3/s, respectively (prototype values). These values were obtained using a debris flow mixture with the grain distribution curve shown on Figure 5. The opening height under the gate of the mixture tank was adjusted to a value of 20 cm.

The preparation of the debris flow mixture to use in the laboratory tests was done using an iterative procedure. Based on Bardou thesis [2], it is possible to predict the debris flow behavior based on its grain size distribution. To produce a granular debris flow, known also as collisional-frictional flow [1], the grain size distribution of the mixture should be within the region 2 shown on Figure 5. It is situated under the Bonnet-Staub border [5] and separates regions of mud flow (viscoplastic) and classical bedload flow. The final grain distribution curve of the mixture used in Bruchji's tests is shown in bold continuous line on Figure 5. On this same Figure and for comparison raisons, some mixture distribution curves that have been used in other laboratory experiments [3, 4 and 12] are also shown. It has to be noted here that the mixture tank was continuously supplied with a 5 m^3/s of water injected near its base. It was equipped with an overflow pipe to keep a constant water level inside it.

The channel roughness, the debris flow mixture and the gate opening height have been validated by comparing the mean values of the tests output parameters h, v and Q_s to other characteristic mean values of some reference works (Table 3).

Since a good agreement was found between these values, no further rheological studies and content modifications were done on the sediment mixture.

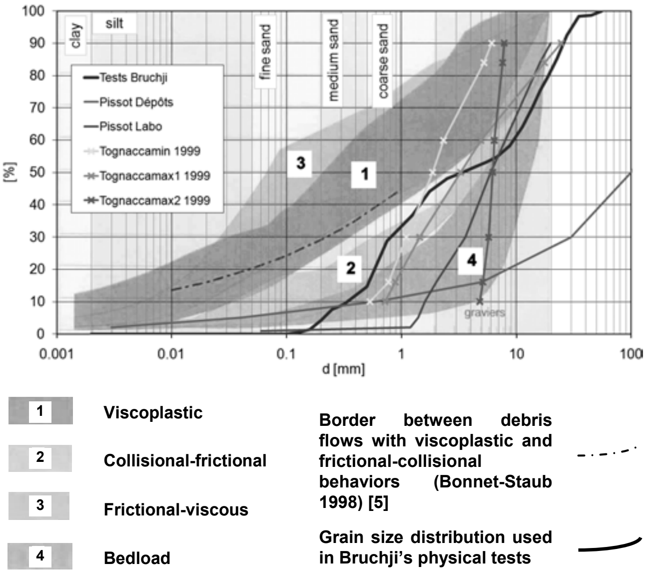


Figure 5. Classification of the behavior of debris flow mixtures according to their grain size distributions [2]. Also shown, six grain size distributions (including Bruchji) for some reference experimental mixtures [3, 4 and 12].

Table 3. Mean characteristic values for debris flows extracted from some reference works

Measured parameters	Variable	Value	Source
Front height	h [m]	1 – 3	Bardou [2]
		1.2	Rickenmann [8]
		1.2 – 3.5	Sinniger [9]
Front wave	v [m/s]	3 – 5	Davies [7]
		5.9	Rickenmann [9]
		1 – 7	Bardou [2]
		5	Takahashi [10]
Discharge	Q_s [m^3/s]	100	Empirical formula $Q_s=0.1\cdot V^{5/6}$ (with V=4000 m^3)
		87	Rickenmann [8]
		60 – 70	British Columbia [6]

2.4 *Measuring devices*

The debris flow depth was measured continuously with eight ultrasonic probes distributed all along the channel length. The first significant change in each probe signal indicates the arrival time of the debris flow head at the probe measurement section. From these measurements, the debris flow parameters can be extracted. The water supply for the model was controlled by a valve and the discharge was measured by an electromagnetic flow meter. Systematically, a topographical survey of the model channel bed was performed after each test. All the experiments were also documented using photos and video recordings. The measuring devices used to quantify the relevant parameters of the experimental study are listed in Table 4.

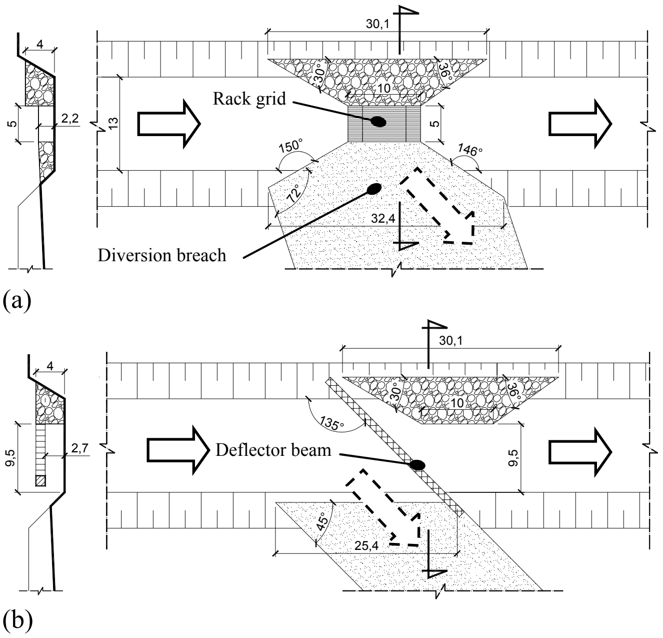
Table 4. Measuring devices and accuracies

Parameter	Instrument	Accuracy level	
		Model	Prototype
Flow level and depth	Ultrasonic probe	± 1 mm	± 2.0 cm
Water discharge	Electromagnetic flowmeter	± 0.25 l/s	± 0.5 m^3/s
Front velocity	Ultrasonic probe + chronometer	± 1 mm ± 0.1 sec	± 4.5 mm/s
Topography	Limnimeter	± 1 mm	± 2.0 cm

2.5 *Experimental procedure and optimized control structure*

The first series of laboratory tests were carried out with the control structure of type A having the dimensions shown on Figure 6a. The height of the debris flow head increases when it reaches the upstream contraction cone of the structure. The flow passes over the grid and looses part of its constitutive water. This mass drainage decelerates the flow and forces the sediment to settle down on the grid. This will form an obstacle to the flow and debris flow is diverted through the lateral breach to the deposition area. A part of the solid mass is also retained in the channel bed at the upstream side of the structure. At the end of the debris flow event simulated by four discrete and identical pulses, clear water is injected inside the model to test the flushing process and the re-opening of the flow section below the rack. A water discharge equal to 5 m^3/s (one year return period flood) was used. The control structure was tested at the two channel positions 1 and 2. The control structure was more efficient in the channel bend position than in the straight channel reach.

The B configuration of the control structure was tested in a second series of laboratory tests (Figure 6b). In this configuration, a unilateral contraction was used inside the channel cross section. It was placed 12 m downstream the bilateral contractions of configuration A. The breach width was also adjusted to a value of 25.4 m measured in prototype scale. To increase the efficiency and the robustness of the structure, an inclined deflector beam was added. The lower level of the deflector was determined as being the level reached by the debris flow deposits after the simulation of the two first surges of debris flow. Tests have shown that the configuration B diverts a debris volume 10 to 15% higher than the A configuration. The scattering of the diverted volumes was also lower in B than in A configuration. So, further on in this paper, only the tests results of the former structure type are presented and discussed in detail.



(a)

(b)

Figure 6. Plan views of the optimized versions of the control structure. a) Configuration A, b) Configuration B. (All dimensions are in prototype scale and are in meters).

According to the design guidelines, not more than 10000 m^3 of debris flow should reach the existing deposit reservoir situated downstream from the control structure after the simulation of four debris pulses. The lower face of the deflector was adjusted to the same level of the sediment deposit generated after the first two successive surges. Thus, debris flow was only diverted during the third and forth debris pulses.

3 TESTS RESULTS

3.1 *Debris flow parameters h, v, and Q_s*

Eight ultrasonic sensors were used to measure the time history of the debris flow heights. Figure 7 shows the output results obtained from these sensors during one test pulse. Sensors from 1 to 4 cover the channel reach situated upstream from the control structure while the four others (5 to 8) cover the downstream reach. Formulae that have been used to determine the debris flow parameters are also depicted on Figure 7. Having as input the relative distances between sensors, the detection of the time lag between the front records allow the estimation of the mean flow velocity v between two successive sensors. From the mean flow depth h measured inside each reach, the mean flow discharge Q_s is deduced.

Figure 7 shows also the longitudinal profiles of debris flow. The typical head and trailing body can be clearly observed in the records of the first four sensors. The dispersion phenomenon has flattened the profiles of the four other sensors.

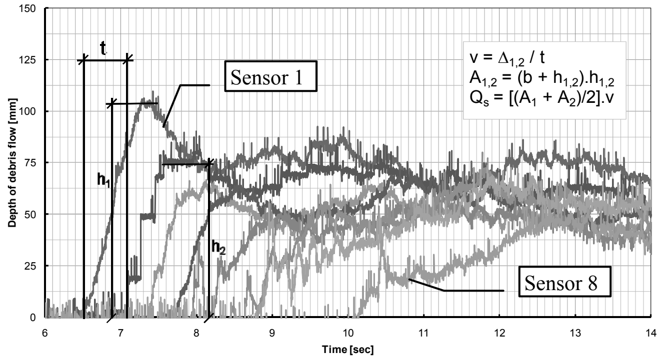


Figure 7. Depth history of debris flow measured by the eight ultrasonic sensors (in model scale).

3.2 *Time evolution of the solid deposits*

The evolution of the deposits depth for a typical four pulses test is shown on Figure 8. The effect of the local unilateral contraction of the channel's section leads to a maximum deposition height near the contraction's entrance. The deposition area extends upstream progressively from pulse to pulse to reach a length of about 50 m (in prototype scale) measured from the contraction section. At the end of the forth debris flow pulse, the total injected volume was equal to 16000 m^3 and the maximum prototype depth's deposit reached 4 m.

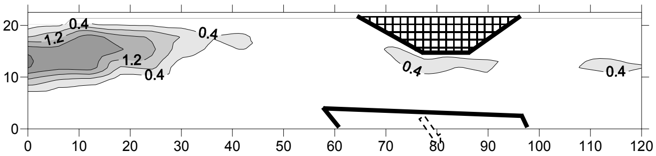
Figures 9 and 10 show two test photos of the sediment deposits at the end of the first and third pulses respectively.

3.3 *Volume balance*

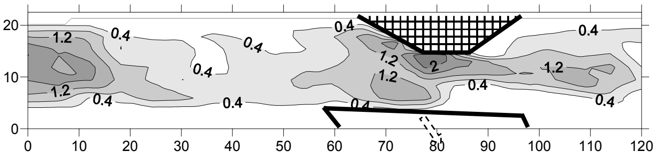
A typical volume balance of the solid materials is shown in Table 4. For the optimized control structure of type B, a volume of about 8500 m^3 of debris flow material can transit through the structure. This volume is below the threshold volume of 10000 m^3. The deposition volume inside the torrent reach at the upstream side of the structure is about 5570 m^3 while the diverted volume is equal to 1860 m^3.

The evolution of the deposition volume from pulse to pulse is given on Figure 11. It is clearly shown that no diversion occurs during the two first pulses. A small amount of materials is deposited upstream the structure. At the third pulse, the diversion volume is near 27% of the pulse volume. The total diverted volume after the fourth pulse is about 12% of the total injected volume. A higher volume percentage (near 35%) is stocked upstream the structure. About 53% of the total injected materials transit downstream. Figure 12 shows the volume balances for four test series of four pulses each. The small variations of volumes between these tests confirm the robustness of the solution adopted.

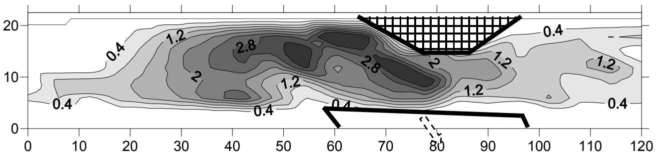
The flushing tests with clear water following the debris flow event have efficiently eroded the alluvial bed. Water flow has returned back rapidly to the bed of the Bruchji's torrent.



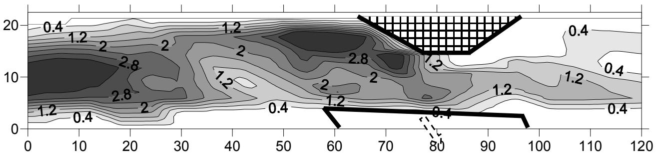
1 Deposition after the first debris flow sequence (Volume of sediments 4'000 m^3)



2 Deposition after the second debris flow sequence (Volume of sediments 8'000 m^3)



3 Deposition after the third debris flow sequence (Volume of sediments 12'000 m^3)



4 Deposition after the fourth debris flow sequence (Volume of sediments 16'000 m^3)

Figure 8. Time evolution of the deposition heights during a typical four successive debris flow pulses of 4000 m^3 of volume each (units in meters and in prototype scale).

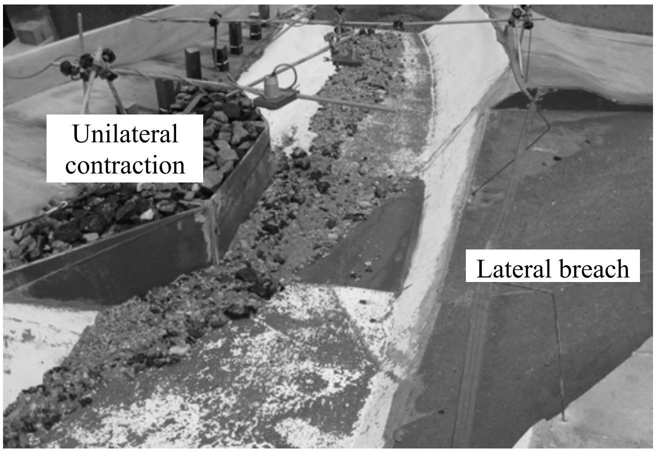


Figure 9. Photo of the model taken from upstream showing the deposits at the end of the first pulse of debris flow.

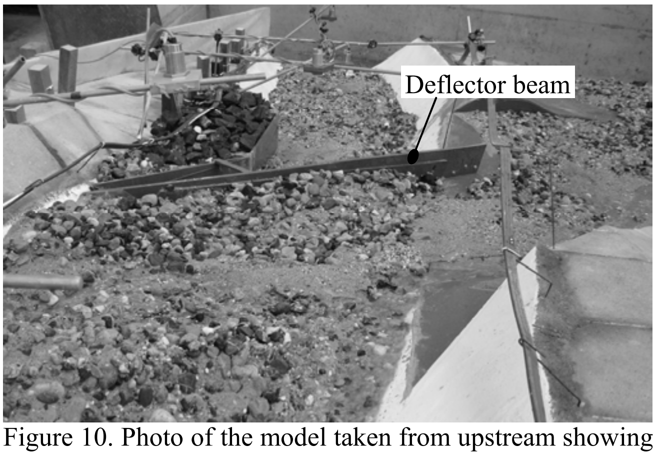


Figure 10. Photo of the model taken from upstream showing the deposits at the end of the third pulse of debris flow.

Table 4. Balance of debris flow volumes during a typical four pulses event of 4000 m^3 each.

Total injected volume, V(in):	16000 m^3
Total transited volume, V(out):	8570 m^3
Total upstream deposited volume, V(stock):	5570 m^3
Total diverted volume, V(div):	1860 m^3

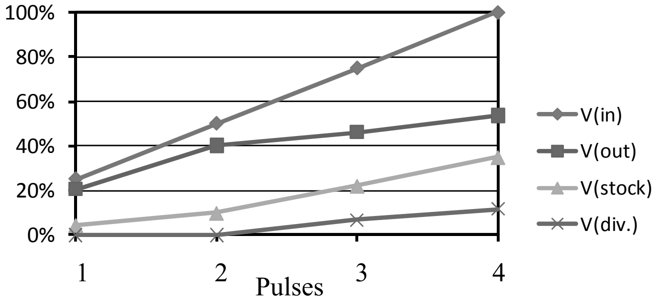


Figure 11. The evolution of the volume distribution percentages of deposit materials during a typical event of four pulses.

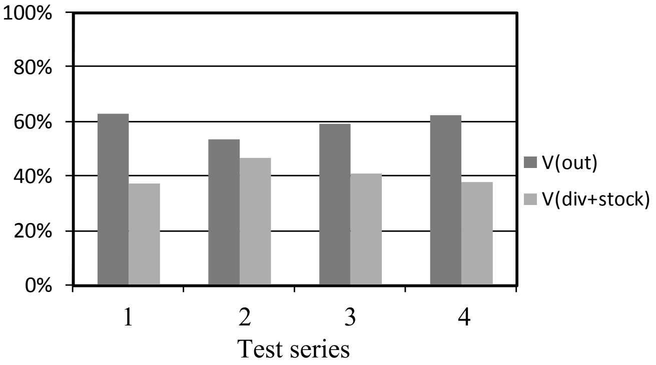


Figure 12. Volume balances for four test series composed each of four pulses.

4 CONCLUSION

The experimental study presented in this paper, has been a very useful tool for designers to optimize their control structure to divert the debris flow events of the Bruchji's torrent. This study has led to the following conclusions:

The control structure should be constructed in the curved part of the Bruchji's torrent (position 2). The centrifugal forces created by the bend effect favorites the diversion of debris flow.

The configuration of the control structure with a unilateral contraction and beam deflector (configuration B) was 10 to 15% more efficient than the bilateral contractions solution with horizontal rack.

The optimized control structure of type B reduces the channel width from 13 to 9.5 m and limits the flow height to 2.7 m below the deflector beam. The width of the lateral breach in the right bank side of the torrent is adjusted to 25.4 m.

During a typical debris flow event composed of four discrete pulses of 4000 m^3 each (event with a return period of 20 years), the total diverted volume will be near 12% of the total event volume. About 35% will be stocked inside the torrent in the upstream side of the structure and near 53% will be transited downstream.

The flushing tests done at the end of the debris flow events have efficiently eroded the alluvial bed formed by the material deposits. After each event, the water flow has returned back rapidly to the bed of the Bruchji's torrent.

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