Stony Debris Flow Debouching in a River Reach: Energy Dissipative Mechanisms and Deposit Morphology

Antonio Fichera, Laura Maria Stancanelli, Stefano Lanzoni, and Enrico Foti

Abstract

Stony debris flows are investigated at the laboratory scale. A set of 11 experiments are carried out, to simulate the stony debris flow propagation in a typical mountain confluence with a downstream water channel. The dynamic of the tributary flow just upstream of the junction with the river, surrogated through the volumetric mixture discharge, is assessed through the analysis of velocity profiles, while observations on deposit morphology provide insight into the condition which cause the blockage of the main stream. Energy dissipation within the solid–liquid mixture is mainly controlled by collisions between grains, and a dilatant fluid model is found to approximately reproduce the velocity profile. The degree of river blockage caused by the delivered material is classified according to three configurations: (i) full blockage, whereby the entire transversal river section is dammed (100% river obstruction); (ii) no blockage when less than 60% of the transversal river section is interested by the deposit; (iii) partial blockage for intermediate damming configurations (>60% and <100% of the river obstruction).

Keywords

Stony debris flow • Confluence • Velocity profile • River damming

Introduction

Stony debris-flows are generated in mountain areas, especially along gullies, when the colluviums and the coarse sediment deposited on the bed are triggered by the water discharge caused by high intensity rainfalls. After the triggering, the loose sediment along the gully are partially or completely incorporated into the flowing mass (e.g. Iverson 2012). In particular, stony debris flows may grow by several orders of magnitude after initiation as they erode material along their flow path before deposition takes place (e.g. Iverson 2012; Hungr et al. 2005). Such phenomena are frequent in the Dolomites (Italian Alps) during the summer period in occasion of high intensity rainfall storms (Berti et al. 1999; Gregoretti and Dalla Fontana 2008).

Various monitoring activities on full scale events have been carried out in such complex environments (Arattano et al. 2004; Berti et al. 2000), yielding for a number of stony debris flow some information about: average velocity and depth of the front, solid concentration and pore pressure (Fig. 1).

Data provided by measurements carried out in the field are crucial for understanding the global dynamics of the phenomena, but are inevitably affected by the specific

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Fig. 1 Example of gully channel, typical of the Dolomites (Italian Alps), filled with coarse sediments that in occasion of intense rainfalls can generate stony debris flows (Fiames, Cortina d'Ampezzo, Italy). Image courtesy of prof. Carlo Gregoretti

constrains of the monitoring site (slope of the channel, sediment features, triggering water discharge) and of the observed events. Therefore, no parametric analysis can be pursued to disclose the influence of single variables.

The aim of the present research is to analyze the interplay of the dynamic forces acting at a confluence (associated with debris flow injection and main river flow), and determining the configuration of sediment deposits along the main channel. The dynamic contribution of the stony debris flow injection is assessed by considering the sediment–water mixture velocity profile, and the deposit shape is studied considering different discharge ratios and a few confluence configurations.

Experimental Setup and Procedure

The experimental apparatus is located at the Hydraulic Laboratory of the Department of Civil, Environmental and Architectural Engineering, University of Padua, Italy. It consists of a tributary flume 3 m long, 0.3 m wide and 0.30 m deep, connected to a main channel of length 12 m, width 0.5 m and depth 0.70 m (Fig. 2). The junction between this flume and the main channel is ensured by a particular joint system which allows variations of both the tributary slope and the confluence angle. The side wall of the tributary flume is made by plexiglass, allowing to film the flow by means of two video cameras (100 fps).

The tributary flume is equipped with an acoustic level sensor (Pepperl + Fuchs, application range 0–0.5 m, error 0.001 m) to measure the time distributions of surface levels.

Stony debris flow is generated by releasing a prescribed water discharge (3.6 l/s) over a loose gravel bed (sediment diameter size 3 ÷ 4 mm) of thickness 9 cm placed in the tributary flume and preliminary saturated (Q_{sat} = 0.8 l/s). The flowing sediment–water mixture is of the stony debris flow type, and its discharge Q_{df}, is responsible of the amount of sediment delivered to the main channel. Eventually, the

Fig. 2 Experimental apparatus consisting in a lateral tributary flume connected to a downstream main channel

Fig. 3 Example (run 9) of the partial blockage of the main channel caused by the debouch of a stony debris flow generated along the tributary channel

sediment mobilized in the tributary flume accumulates in the main channel (see Fig. 3), and its deposit is shaped and reworked by the water discharge (Q_w) flowing in the main channel.

At the end of each experiment a survey of the sediment deposit is carried out in order to its shape and size.

Experiments

A set of 11 experiments has been carried out, as summarized in Table 1, which reports the relevant parameters of each test. In particular, we considered two debris flow discharges in the tributary flume (Q_{df} = 7 and 9 l/s), three water discharge along the main channel (Q_w = 4.5, 3 and 2 l/s), and three confluence angles (α = 60–85–90°).

Experimental observations of velocity profiles throughout the depth of the propagating sediment–water mixture are important for characterizing the energy dissipation mechanisms acting within a debris flow. In particular, as it propagates downstream, the mixture typically exhibited, in sequence, a steep front propagating downstream, a body with an almost constant depth, and an elongated tail (Stancanelli et al. 2015).

The erosion of the loose gravel bed initially located on the tributary channel, is essentially concentrated during the passage of the tail, while the body is characterized by a nearly steady state, with small erosion. Indeed, the flow in the body is characterized by an upper layer, dominated mainly by a collision dissipation mechanism, and a lower layer where energy dissipation is of the frictional type.

Table 1 Summary of the relevant parameters characterizing the present tests

Run (no.)	Q_{df} (l/s)	Q_w (l/s)	α (°)
1	9	4.5	90
2	9	4.5	60
3	7	4.5	60
4	7	4.5	85
5	9	4.5	85
6	7	4.5	90
7	7	2.0	90
8	9	2.0	90
9	9	2.0	60
10	9	3.0	60
11	9	3.0	90

Symbols are as follows: run number; Q_{df}, volumetric stony debris flow discharge determined 30 cm upstream of the tributary outlet of the tributary channel as the product UD of the depth averaged velocity U and the flow depth D; Q_w, volumetric water discharge along the main channel; α, confluence angle

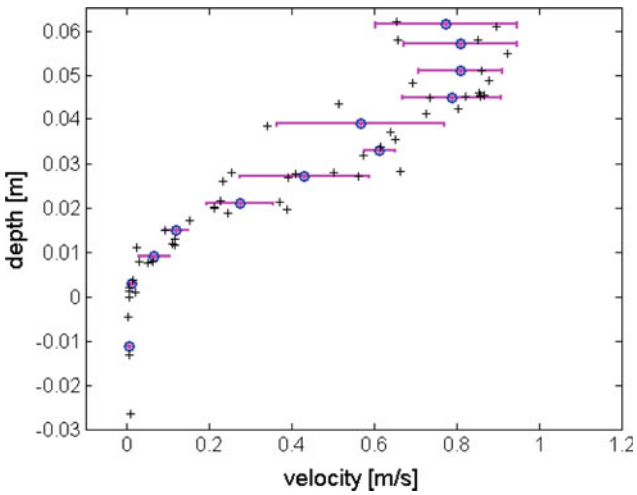

Fig. 4 Velocity profile in the debris flow body, reconstructed along the normal to the flow 30 cm upstream of the tributary flume outlet. The corresponding stony debris flow volumetric discharge, calculated as the product UD of the depth averaged velocity U and the flow depth D, is Q_{df} = 9 l/s. *Black crosses* denote single particle velocities, while *blue circles* refer to the mean velocities calculates in layers of thickness 0.6 cm. *Magenta lines* indicate the standard deviation of the layer averaged velocities

Figure 4 shows an example of the velocity profile that establishes in the body, surveyed in a section located 30 cm upstream of the outlet of the tributary channel. The velocities have been reconstructed by means of an image analysis technique, based on particles recognition and tracking, that estimates the displacement in time of observed gravel particles (time difference between each frame is 0.01 s). It clearly appear the presence of two layers: the upper with larger fluctuation of particle velocities due to frequent collisions; the lower with relatively small velocities, owing to the long-lasting contacts between particles. As a consequence, the velocity profile is characterized by a double curvature: down looking in the lower layer (of thickness about 2 grain diameters) and up looking in the upper layer. Note that negative values of the flow depth correspond to the loose static sediment over which the body of the debris flow propagates.

Information about deposit morphology is acquired at the end each experiment. For a particular confluence configuration (confluence angle), the type of sediment deposits results from the dynamic interaction between the stony debris flow discharge debouching in the main channel and the water discharge flowing along it. This water discharge, depending on the considered conditions, can: (i) wash out completely the sediment delivered by the stony debris flow (no dam formation); (ii) partly erode the sediment deposit (partial blockage); (iii) create an impoundment upstream the sediment dam (total blockage).

It is important to point out that in the present research we consider as deposit the mass of sediment with an elevation higher than 5.5 cm. This allows us to define objectively the main features (volume and shape) of the deposit core, neglecting the marginal areas, that are subject to a continuous interaction with the main channel flow.

Figure 5 reports some sketches and typical examples of the possible partial and total blockage configurations attained in the experiments. In particular, we denote as: no blockage a planform configuration whereby the gravel deposit has a maximum linear extension in the transverse direction less than 60% of the main channel width (Fig. 5a); partial blockage a gravel deposit with a lateral linear extension in the range 60–100% of the main width (Fig. 5b); total blockage when the gravel deposit occupies completely the transversal section of the main channel (Fig. 5c).

Results

The analysis of the velocity profiles observed along the tributary provides information about the relevant dissipative mechanisms and an estimate of the volumetric discharge carried by the sediment–water mixture, Q_{df}.

The velocity profile presented in Fig. 4 clearly indicates the existence of two layers with different dissipative mechanisms. In the upper one, dissipation is essentially due to collisions between grains. The dilatant rheological model proposed by Takahashi (2007) then gives a reasonable description of the order of magnitude of the observed velocities (see Fig. 6). However, a dilatant model is not able to describe the velocities that establish in the lower flow layer, near to the loose erodible bed. Therein the long lasting contacts between sediment particles imply the predominance of frictional forces. Note that the velocity profile show in Fig. 6 not only entails a collision dominated behavior, but has also been computed by assuming a constant concentration in the dilatant rheological. As a consequence, the effects of the lower boundary condition (erodible bed) cannot be accounted for. In any case, the information about the magnitude of the depth averaged velocity is fundamental to estimate the volumetric discharge Q_{df} conveyed by the stony debris flow. Indeed, the discharge ratio $R_q = Q_{df}/Q_w$ (Dang et al. 2009), together with the confluence angle α are relevant parameters that control the degree of channel obstruction.

Figure 7 presents the degree of channel obstruction (no blockage, partial blockage and total blockage) as a function of R_q and α. As expected, a lower value of R_q indicates an higher erosive action of the water flowing in the main river, favoring the washing out of the sediment delivered by the debris flow. In particular, for $R_q < 2$ no blockage is observed

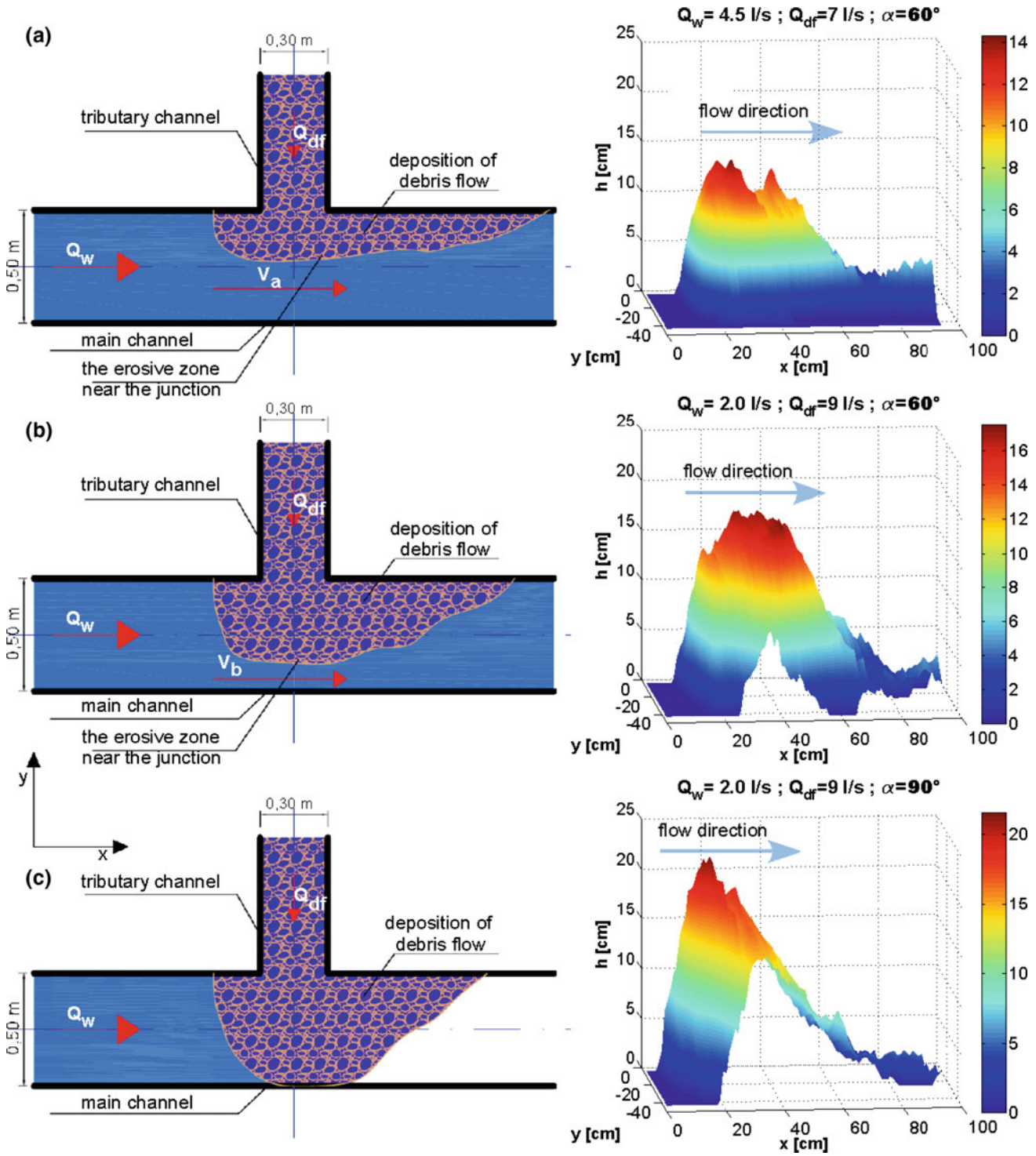

Fig. 5 Possible blockage configurations observed in the main channel due to the sediment injected laterally by a stony debris flow: **a** no blockage (maximum linear extension of the deposit in the transverse direction <60% of the main channel width); **b** partial blockage; **c** total blockage. For each configuration, the *left panel* shows a sketch of the planform deposit shape, while the *right panel* reports the measured deposit elevation

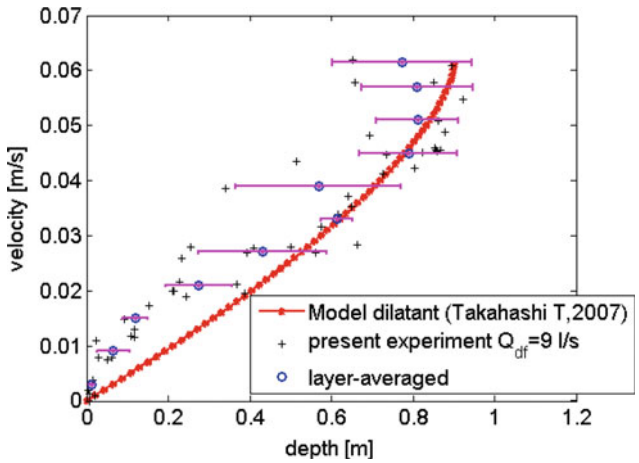

Fig. 6 The observed velocity profile shown in Fig. 4 is fitted by using the dilatant rheological model of Takahashi (2007)

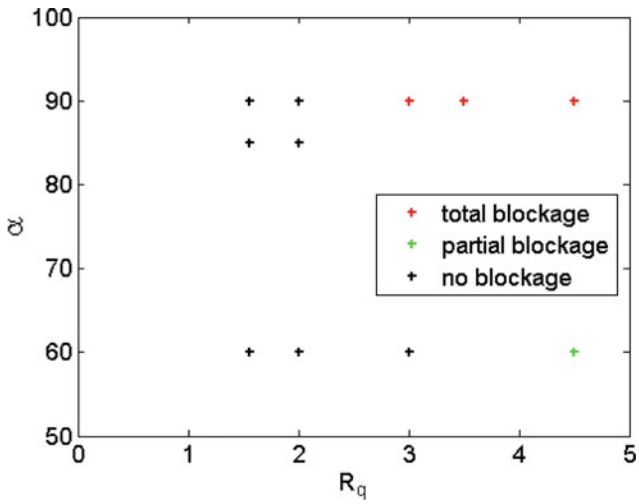

Fig. 7 Blockage conditions of the main channel section acquired for the tests of the experimental campaign. Results are presented in relation of the discharge ratio parameter (R_q) and the confluence angle (α)

in the tests, independently of the considered inclination angle. Conversely, the angle α plays some role for $R_q > 2$.

For example, in the case of $R_q = 3$ a low confluence angle (60°) implies no blockage conditions, while total blockage is observed while total blockage is observed for $\alpha = 90°$. As expected, higher values of the confluence angle enhance the probability of observing a stable deposit along the main channel.

Clearly, the present results refer to a limited range of the discharge ratio (ranging in the interval 1.6–4.5), implying that the volumetric discharges in the main channel and in the tributary flume are of similar order of magnitude. This is, however, the condition that entails a more difficult prediction of the degree of obstruction. In fact, very large water discharges in the main channel as compared to the debris flow discharge enhance a rapid sediment flushing that ensure the clearance of the main channel section. Conversely, significantly high debris flow discharges with respect to the main channel flow invariably determine the damming of the main channel.

Conclusions

The morphology of sediment deposits produced by a debris flow debouching in a main river reach is the results of the equilibrium between two hydrodynamics forces (surrogated by the volumetric discharges associated to the debris flow injection and main river flow) and of the geometry of the confluence.

In the present contribution we analyzed the problem through flume experiments, focusing our attention on stony debris flow. In particular, we used the observed stony debris flow velocity profile for estimating the corresponding volumetric discharge. This value is used to determine the ratio with respect to the water discharge flowing in the main channel which is then related to the shape of the observed sediment deposits.

The velocity profiles measured within the debris flow body indicate that a collision dominated behavior, typical of stony debris flows, prevail within the upper portion of the sediment–water mixture column, whereas a rheological regime dominated by friction prevails near the loose static sediment bed. A dilatant rheological model (Takahashi 2007) then provides a reasonable estimate of the order of magnitude of the velocities, but not describes thoroughly the velocity distribution along the debris flow depth.

The observed debris flow velocity profiles are used to compute the corresponding volumetric discharge Q_{df} that is used in comparison with the water discharge in the main channel Q_w to characterize the type of sediment deposit that forms in the main receiving channel. Three morphological configurations of the deposit have been observed: (i) no blockage, (ii) partial blockage; (iii) total blockage of the river section. The present flume tests indicate that no blockage invariably occurs for values of discharge ratio $R_q = Q_{df}/Q_w$ lower than 2, independently of the value attained by the confluence angle α. In general, higher confluence angles produce a higher degree of obstruction in the main channel and determine a decrease of the value of the discharge ratio for which partial/complete blockage takes place. For the material adopted in the present experiments, total blockage is observed for $R_q \geq 3$ at high enough confluence angles (=90°), while for lower confluence angle (=60°) and R_q in the range to 4.5 only partial blockage is observed.

Future work will analyze the influence in the dam formation of the sediment material and the grain size distribution of the stony debris flow.

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References

Arattano M, Franzi L (2004) Analysis of different water-sediment flow processes in a mountain torrent. Nat Hazards Earth Syst Sci 4:783–791

Berti M, Genevois R, Simoni A, Tecca PR (1999) Field observations of a debris flow event in the Dolomites. Geomorphology 29:265–274

Berti M, Genevois R, LaHusen R, Simoni A, Tecca PR (2000) Debris flow monitoring in the acquabona watershed on the dolomites (Italian alps). Phys Chem Earth (B) 25(9):707–715

Dang C, Cui P, Cheng Z (2009) The formation and failure of debris flow-dams, background, key factors and model tests: case studies from China. Environ Geol 57:1901–1910. doi:10.1007/s00254-008-1479-6

Gregoretti C, Dalla Fontana G (2008) The triggering of debris flow due to channel-bed failure in some alpine headwater basins of the dolomites: analyses of critical runoff. Hydrol Process 22(13): 2248–2263

Hungr O, McDougall S, Bovis M (2005) Entrainment of material by debris flows. In: Jakob M, Hungr O (eds) Debris-flow hazards and related phenomena. Springer, Berlin, pp 135–158

Iverson RM (2012) Elementary theory of bed-sediment entrainment by debris flows and avalanches. J Geophys Res 117:F03006. doi:10.1029/2011JF002189

Stancanelli LM, Lanzoni S, Foti E (2015) Propagation and deposition of stony debris flows at channel confluences. Water Resour Res 51 (7):5100–5116

Takahashi T (2007) Debris flow, mechanics, prediction and countermeasures. Taylor & Francis, London, 46 p. ISBN: 978-0-415-43552-9