The debris flow event of 29 October 2018 in the Rio Rotiano (Italy) and its challenges for the mathematical and numerical modelling

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Abstract. The debris flow that interested the Rio Rotiano, a creek located in the Province of Trento (Italy) on 29 October 2018, is an event that, because of its peculiar features, presents formidable challenges in terms of mathematical and numerical modelling. Here we present some results of our research, which required both physical and mathematical modelling, aimed at developing a numerical tool necessary to face the back analysis of the event and the validation of the planned protection works. Exploiting some results of the laboratory tests and coupling an advanced description of the debris flow dynamics (TRENT2D model) over fixed and mobile bed with a sub-surface flow model, we obtained a model that can be defined as a mobile-bed rainfall-runoff model, where the runoff is composed by both water and sediments and represents a new paradigm in the field of debris flow simulations. First applications give promising results but some further developments are required before completing the back analysis of the Rio Rotiano event.

1 The Vaia storm and its effect on the Rio Rotiano

From 26 to 30 October 2018, the northeast part of Italy was hit by an Atlantic extreme storm, called Vaia, with intense rainfalls and very strong winds. In addition to the felling of about 42 million trees, one of the most severe damages caused by the storm occurred along the Rio Rotiano (Provence of Trento, Italy) on 29 October, because of a debris flow.

Fig 1. Remnants of two destroyed check dams along the Rio Rotiano.

What characterized this debris flow was the fact that it affected almost the whole length of the creek but, above all, that most of the protection works present along the river shaft were damaged (Fig. 1): 2 slit check dams and 16 closed check dams of different shape and constructive characteristics collapsed or was heavily damaged, releasing the sediments present in the relevant upstream storage areas. This phenomenon led to large erosions in the upper part of the creek and deposition in the alluvial fan, where the debris flow overtopped the banks and hit the village (Fig. 2).

Fig. 2. Aerial view of the consequences of the debris flow developed in the Rio Rotiano on the village of Dimaro.

2 Back analysis and design of protection works: two sides of the same coin

Besides emergency restoration works, soon after the event the Servizio Bacini Montani, the public service

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that oversees the management of the mountainous territory of the province of Trento, had to face the problem of understanding, on the one hand, what happened along the creek and, on the other hand, of verifying the capabilities of the planned protection works to reduce the hazard to an acceptable level. To face this difficult task, a team, composed of three different research institutions (TESAF, University of Padua; CNNR IRPI and our institution), has started working on it. Our role has been to develop a mathematical and numerical tool capable of tackling the problems and performing the relevant simulations. In this contribution, we want to present the efforts we have made, and are still making in this direction.

The back-analysis of this event presents formidable difficulties because of the complexity of the phenomena involved and because we know very little of what happened along the creek, in particular, when and why each dam collapsed. Available data regard some altimetric features (the DTM and the DSM surveyed after the event and a DTM surveyed some years before the events), the estimated volume of sediments involved in this event (about 170000 m^3), an orthophoto of the whole basin, taken the days after the event (useful for mapping the extension of the involved area), data from a rain gauge located 5 km from to the upper part of the Rotiano basin (showing a peak of rain of 36.5 mm/hour lasting for 40 minutes around 19:00) and, finally, testimonials indicating the occurrence of three distinct pulses of debris flow (indicatively occurring at 19:00, 19:50 and 23:30).

As for the protection works, a complex system of open check dams in the upper part of the stream and a channel, running through the village, paved with tied boulders immersed in concrete was planned.

3 The challenges for the mathematical and numerical modelling

When we started to analyse this event, it immediately appeared that the numerical tool we had at our disposal to model this debris flow, i.e., the TRENT2D model [1], despite its advanced features (two-dimensional, two-phase description of the mixture flow over a mobile bed), was insufficient to describe such a complex situation, even in its main features. Therefore, a significant improvement was needed to address what we considered to be the most important phenomena to be simulated, present in both the back analysis and the validation of the protection works. These phenomena, and the relevant modelling, are described in the following two sections.

3.1 Debris flow over a non-erodible bed.

In the Rotiano creek, while for almost the entire stretch the flow runs on a mobile bed, where both erosions and depositions may occur, just before reaching the alluvial fan, the flow passes through a rocky, sinuous gorge, about 500 m long. During the event, in this reach, erosion of a thin layer of about 0.5m of soil present before the event and deposition of material in some bends occurred. Similar flow and deposition conditions were expected along the designed paved-bed channel. For this reason, a model was needed that could only erode the bed to a certain level and, under certain other conditions (to be determined), deposit on it. In other words, the model should have been able to switch from mobile to non-erodible bed conditions and vice versa. Though a numerical algorithm has already been developed for the 1D case [2], a 2D extension and some laboratory data to validate the model were required. Therefore, since no data were available in the literature concerning the limit conditions beyond which there is a switch between the fixed and mobile-bed conditions, we performed some experiments in a flume and derived an empirical relation (see Section 4). Moreover, we built a physical model of the Rio Rotiano comprising a part of the rocky, sinuous gorge, the waterfall and the channel designed to protect the village, which we used, among other things, to validate the numerical model (Section 5).

3.2 A rainfall-runoff model comprising the debris flow formation

Since in the Rio Rotiano basin the debris flow affected almost the entire length of the creek, the debris flow model should have considered the distributed increase of the liquid phase due to the rainfall contribution connected to the superficial flow. Moreover, because of the geological characteristics of the basin, the model should have also considered the sub-surface flow as a source of water. However, during the event, due to the large erosions that occurred, the sub-surface flow must have undergone large changes compared to the initial condition of the bed. Therefore, unlike common modelling where runoff can be evaluated by considering the bed as fixed, the model should have coupled the debris flow dynamics with the sub-surface model. The resulting model was to become a *mobile-bed rainfall-runoff* model, in which the runoff would be both solid and liquid. The characteristics of this model are briefly presented in Section 5.

4 The limit values of the solid discharge on a fixed bed

To obtain the empirical relation expressing the limit conditions beyond which there is a switch between the fixed and mobile-bed conditions we carried out some experiments in a tilting flume in which the bed was made of sand particles glued on the bottom, to form a rigid bed. As for the solid particles, we used PVC cylinders about three times bigger than the sand. Each run was performed considering a given value of the bed slope of the flume and a uniform flow condition. Feeding was done with a constant value of water while the solid discharge was increased, step by step, passing from fixed bed to mobile bed transport. At each step, the Shields stress was calculated by measuring the mixture depth.

The results of some of these runs are shown, with coloured symbols joined with lines, in Fig. 3, where the dimensionless sediment discharge $\hat{q}_s = q_s/(d\sqrt{g\Delta d})$ is plotted versus the Shields stress $\hat{\tau} = \tau_0/(\rho_w g\Delta d)$, where q_s is the solid discharge, d is the diameter of the sediments, g is the gravity acceleration, $\Delta = (\rho_s - \rho_w)/\rho_w$ is the solid relative submerged density, ρ_s and ρ_w are the densities of sediments and water respectively and finally τ_0 is the bed shear stress. Each colour refers to a different bed slope.

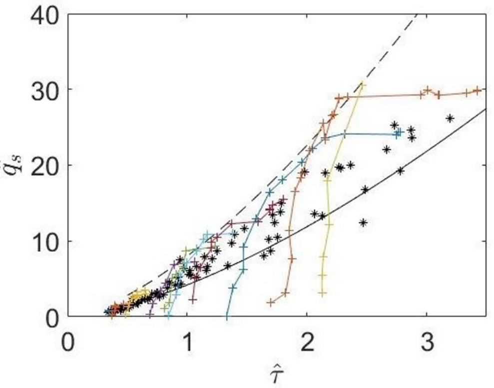

Fig. 3. Nondimensional discharge vs Shield stress. The meaning of the symbols is given in the text.

As the solid discharge increases, also the Shield stress increases. Hence, the solid lines with a given colour move bottom-up and left-right in the plot. They develop till the maximum solid discharge is reached, and then collapse to the mobile bed conditions. The maxima are approximated by a Meyer-Peter Müller relation (dashed line in the figure) whose numerical constant is about twice the value (solid line) employed to approximate the mobile-bed values (black stars). In other words, the maximum solid discharge over rigid bed reaches values about 50% higher than the transport capacity relevant to the same Shields value.

On the contrary, the results of other simulations show that when the roughness of the rigid bed tends to be about the same or bigger than the size of the transported particles, then the maximum discharge over the rigid bed and the capacity transport coincide.

5 Physical modelling and comparison with numerical modelling

The physical model (Fig.4) was obtained by imposing the Froude similarity, (which intrinsically induces the respect of the Shields stress, $\hat{\tau}$). The geometric scale, applied to both the domain geometry and the grain-size distribution, was assumed equal to 1:30 (model:real).

In the physical model, we worked out several runs, with controlled and measured liquid and solid discharges at the upstream end, measurements of the surface velocities and flow depth in a cross-section, and topographical DEM over the entire model at the end of any run. They were used mainly to study the characteristics of the waterfall while one of these runs was used to validate the TRENT2D numerical model in which, the empirical relation described in the previous section was introduced.

Fig. 4. Overview of the physical model.

Considering all the uncertainties present in the measurements and in the model, the results, shown in Fig. 5, show a satisfactory agreement.

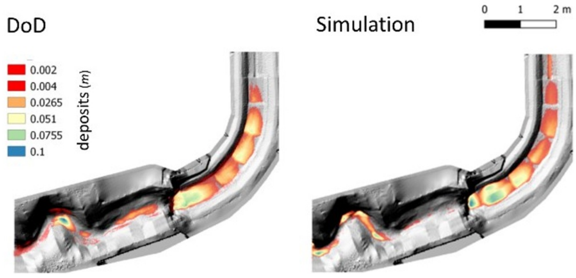

Fig. 5. Comparison between the DoD of the physical model and the simulation obtained with the numerical model. Flow is from left to right upwards.

6 The mobile-bed rainfall-runoff model

The model addressed to simulate the mixture discharge formation starting from the rainfall input is composed of a set of partial differential equations describing, in a coupled way, the sub-surface flow and the superficial flow that can consist of water (in the upper parts of the basin) and in a mixture of water and sediments from the points in which the debris flow initiates to the end of the basin. Due to lack of space, the relevant partial differential equations, the algebraic closure relations, and the numerical schemes employed are not reported. For sake of simplicity, the complete model can be divided into two submodels that are briefly described in the following sections.

6.1 The surface flow (sub)model

This model is none other than the TRENT2D model with the features presented in the Section 3.1, in which a source term is considered, expressing the direct contribution of rain, a possible source term resulting from the water upwelling from the sub-surface model and a sink term expressing the infiltration by using the Green-Ampt expression. In the upper part of the basin, the flow takes place over a non-erodible bed without sediment. This feature can be faced by the TRENT2D model by imposing a non-erodible condition and no sediments coming from upstream. When the bed shear exceeds a certain threshold, the model automatically switches to movable bed conditions, except in areas explicitly designated by the user as non-erodible (with a possible initial erodible layer).

6.2 The sub-surface (sub)model

The model describes the flow by using the 2D water mass balance equation where the velocity is expressed with the Darcy law. Referring to Fig. 6, where for the sake of simplicity a 1D vertical section is reported, it can be seen that the model considers a source term given by the superficial models (the Green-Ampt infiltration f) while a sink term allows transferring some water towards deep runoff (f_{deep}). When the depth of the sub-surface water equals the depth of the soil, a sink term transfers water from the sub-surface to the superficial model (upwelling term f_{upw}). The position of the bed is dynamic, in compliance with the result of the mobile-bed surface flow model.

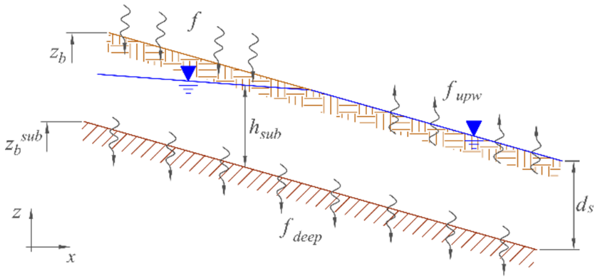

Fig. 6. Sketch of a 1D vertical section of the sub-surface flow model with the indication of the relevant variables.

6.3 Coupling the models

Because of the different spatial scales characterizing the two submodels, two different grid resolutions are employed: the sub-surface flow is evaluated on a coarser grid while the surface mobile-bed model is evaluated on a finer grid, necessary to describe the details of the bed surface geometry. Equations are integrated by using an explicit finite volume method with Godunov fluxes while the spatial coupling is obtained by using an extension of the overlapping grids methods.

6.4 A preliminary application

To evaluate the mobile-bed rainfall-runoff model capabilities, we performed some preliminary simulations on a different basin with respect the Rio Rotiano (namely, Ru d'Alberch, BL (Italy)), characterized by the absence of protection works.

Fig. 7 shows a comparison of the results obtained with a classical fixed-bed and the new mobile-bed rainfall-runoff model. The difference in the liquid discharge as a function of time is evident, both in terms of discharge values and in terms of times, highlighting the importance of considering the effect of debris flow dynamics in the formation of the response of a basin to an extreme rainfall event and, on the contrary, the effect of the coupled hydrology on the debris flow development.

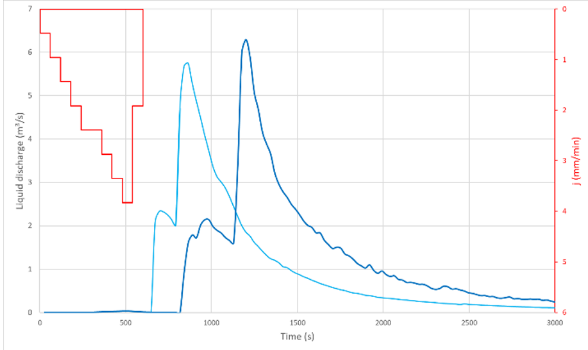

Fig. 7. Comparison between the discharges obtained with a fixed-bed (light blue) and a mobile-bed (blue) rainfall-runoff model.

7 Conclusions

Although the results of the model we have developed so far are promising, there is still much work to be done before completing a back analysis of the Rio Rotiano event. In addition to a demanding calibration of the parameters, a modelling approach needs some further developments to describe the release of debris and water due to the collapse of a dam. The work is undergoing, and we are confident to find a simple, but reliable, way to do that.

In conclusion, we think that even if the challenges connected to the study of the Rio Rotiano debris flow are not completely won yet, the development of the mobile-bed rainfall-runoff model introduces a new paradigm in the field of debris flow simulations to be used, after suitable validation, both in back analysis and in hazard assessment.

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