Bridge obstruction caused by debris flow: a practical procedure for its management in debris-flow simulations

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Abstract. Bridge clogging due to a debris flow is a phenomenon scarcely studied but critical in hazard mapping in the mountain area. Since a rational and systematic approach is still missing, we propose a practical method to deal with this phenomenon in a numerical framework. We tested this methodology by using, as a numerical model, the two-phase, mobile-bed model TRENT2D and, as a site test case, the village of Voueces in the north-west part of the Italian Alps. The application shows reasonable results and highlights the importance of a mobile-bed approach.

1 The role of bridges in determining debris flow hazard in mountain rivers

Mountain valleys are usually carved by streams that, in case of heavy rainfall phenomena, can be affected by debris flows or hyper-concentrated flows. In anthropized areas, roads often cross the rivers with bridges which, in case of extreme events, can induce large deposits of sediments. These phenomena produce a rising in the bed level and the stony (and possibly wood) debris can clog the bridge section with a consequent massive overflow. This situation is very dangerous and, in terms of territorial hazard, potentially even worse than a destroyed bridge.

In Aosta Valley, a region located in north-west side of the Italian Alps, the problem of bridge occlusion due to debris flow is quite common and causes large damages to infrastructures and, if the bridge occlusion occurs in the villages, also to buildings and cultivated areas (Figure 1).

Fig. 1. Consequences of a bridge clogging in the village of Voueces, Ollomont municipality (AO, Italy), following the debris flow event of August 2017.

While the clogging caused by wood debris is a topic recently tackled in the scientific literature [1-3], the clogging caused by stony debris flows is far less studied and the mechanism and the conditions of occurrence are still largely unknown. Due to this lack of knowledge, this scenario is rarely considered for the design and verification of the hydraulic section of a bridge, leading to a potential underestimation of the hazard induced by such structures when a debris flow occurs. In fact, the maximum level of the flow in the section of a bridge was commonly calculated (and is still calculated) assuming a fixed bed condition and a water-only discharge equal to the peak discharge of the relevant debris flow.

The fixed-bed approach is largely insufficient and does not guarantee a good level of safety at least for the following reasons:

- The flow resistance of a debris flow is far larger than the resistance of clear water therefore, at the same flow rate, debris flow depths are larger than pure water depths.
- Clogging often occurs after significant sediment deposition in the bridge section but a fixed-bed approach is unable to describe this phenomenon.
- In a water-only condition, when the flow level exceeds the lower level of the deck of a bridge, water can flow in a pressure regime. On the contrary, in the debris-flow case, a pressure regime is highly unlikely (though not impossible since field evidence shows that, for a small period, it could happen) while a clogging could likely happen.

Both the fixed-bed water-only scenario and non-obstruction one can produce a potential underestimation of the debris flow hazard maps near mountain streams crossed by bridges. Despite the lack of a rational theory, a reasonable practical approach for simulating the effects of bridge obstruction in debris flow simulations is highly advisable.

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2 A practical methodology for the simulation of a bridge clogging scenario

The identification of clogging conditions on a bridge is rather difficult, as it depends on many factors that can hardly be defined a priori.

To tackle the problem within the framework of a debris-flow numerical simulation, in this study we assume that clogging occurs when the flow reaches a level equal to or slightly above the lower level of the bridge for a reasonable period (about ten minutes) and that the deposition under the bridge is, at the same period, such that the free span has the same order of magnitude of the biggest sediments transported by the flow (about three times the quantile 90% of the channel grain size). We call the time at which this situation occurs the conventional time of possible occlusion and denote it by the symbol t_o. From this time onward, since the bridge deck consists of concrete or another hard surface that commonly is not eroded (bridge collapse is commonly linked to other mechanisms), the bridge's upper surface can be considered as a non-erodible bed level having an elevation equal to the elevation of the road. Furthermore, when a bridge is clogged by a debris flow, the observations suggest that the obstruction can only be removed mechanically (e.g., with an excavator as in Figure 2). This means that, once the clogging is formed, the mixture will flow over the deck of the bridge for the remaining instants of the event.

Fig. 2. Mechanical removal of the clogging occurred during the debris flow event of August 2018 in Val Ferret, near Courmayeur (AO, Italy).

We have implemented this procedure by using the TRENT2D model [4] that, in its more recent version [5-7], can deal with both mobile bed conditions and non-erodible bed conditions. Since the model does not automatically set up this type of scenario, it is necessary to produce it “manually”, dividing the overall event simulation into two separate simulations, carried out in cascade as follows:

1. A whole mobile-bed simulation is performed in which the bridge deck is not considered.
2. The time evolution of the free surface and bottom elevation near the bridge cross-section, where clogging may occur, is analysed.
3. If the conventional conditions for occlusion, described above, are reached, then the t_o instant can be identified.
4. The second simulation is then prepared, in which the initial elevation of the computational domain is set equal to the elevation of the bottom reached at the t_o instant in the previous simulation. The elevation, where the bridge is located, is set equal to the upper level of the deck.
5. If in the mobile-bed simulation there are zones with limited erodible thicknesses, the initial values for this second simulation are set equal to the sum of the erodible thicknesses of the mobile-bed simulation and the values of excavations and deposits that occurred up to the t_o instant. A null erodible thickness is imposed on the bridge area, making it non-erodible.
6. The hydrograph of the second simulation is created starting from the one related to the mobile-bed simulation and deleting all the instants before t_o (i.e., taking only the instants between t_o and the end).

The overall simulation is then given by the succession of the mobile-bed simulation, between the initial time of the hydrograph and the instant t_o, and the simulation with obstruction, between t_o and the final instant of the hydrograph.

3 Application to the Voueces village study case

As a test case, we used the village of Voueces (AO, Italy) which was subject to a debris flow event in August 2017 (Figure 1). Since the purpose is not to perform a back analysis of the event that occurred, but to verify if and how the presence of a bridge clogging modifies the flooding area, as forcing conditions we used a mixture hydrograph associated with a return period of 100 years. We performed three different types of simulation:

- *Fixed-bed simulation* where the mixture was considered as pure water flowing over a fixed bed condition. In this case, the presence of the bridge deck was not considered.
- *Mobile-bed simulation* where the mixture was considered as composed of water and sediment flowing over a mobile bed condition. Again, the presence of the bridge was not considered.
- *Obstruction scenario simulation* where the procedure described in section 2 was carried out.

The first results analysis we performed was the comparison between the fixed-bed simulation and the mobile-bed simulation. These results are mapped in Figure 3 where the extensions of the two inundated areas are drawn in different colours. The area obtained with the mobile-bed simulation is around 50000 m^2 while, as expected, the results obtained with the pure-liquid, fixed-bed assumption are considerably different since, in this case, the discharge overtops the banks only in a very limited area and with limited depths, producing a 40% less inundated area (about 30000 m^2).

The second analysis we performed was to test whether the results obtained with the obstruction scenario simulation can be reasonably employed in hazard mapping work.

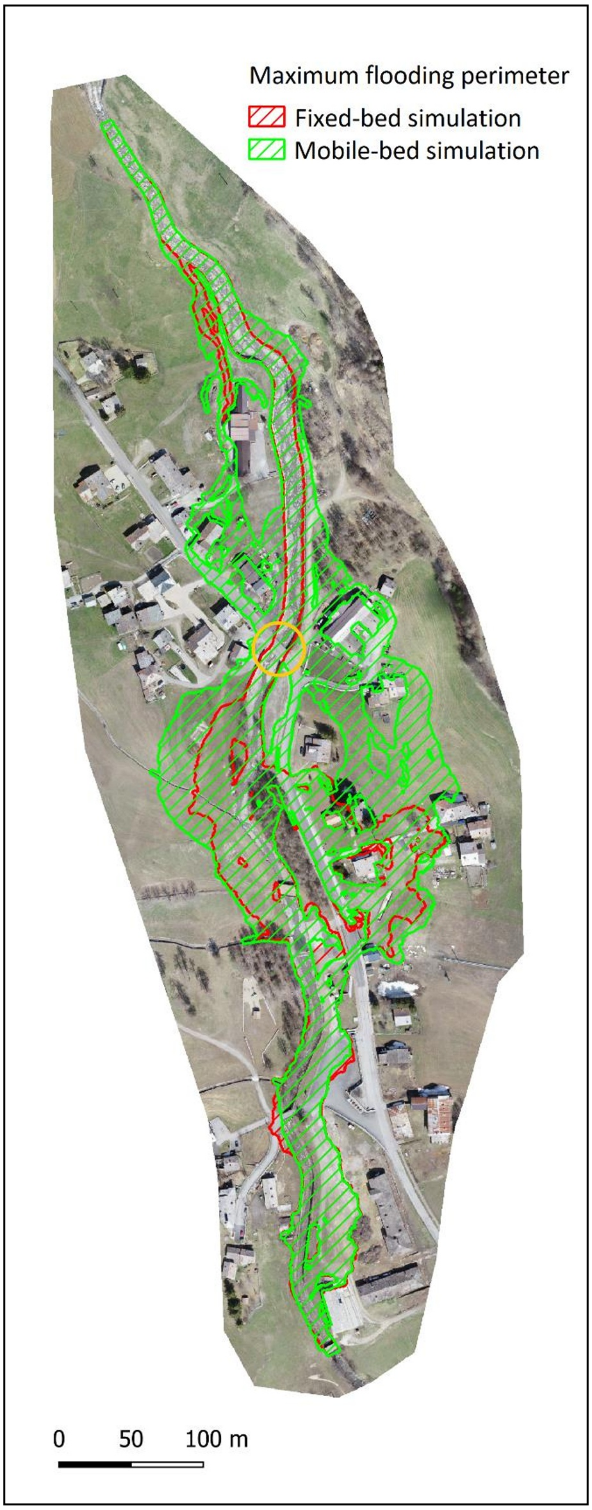

Fig. 3. Comparison of maximum flooding area obtained with the fixed-bed simulation and the mobile-bed simulation. The circle highlights the position of the bridge. Please refer to the text for the meaning of the simulations.

For this purpose, a comparison between the mobile-bed simulation and the obstruction scenario was carried on. These results are shown in Figure 4 where the two maximum inundated areas are drawn in different colours. The effect of the bridge clogging leads to a larger inundated area of about 62000 m^2 than the mobile-bed case even if, in this specific case, it is not striking (24% increase). This is due to the large deposition phenomenon occurring, anyway, near the bridge area caused by a significant decrease in bed slope.

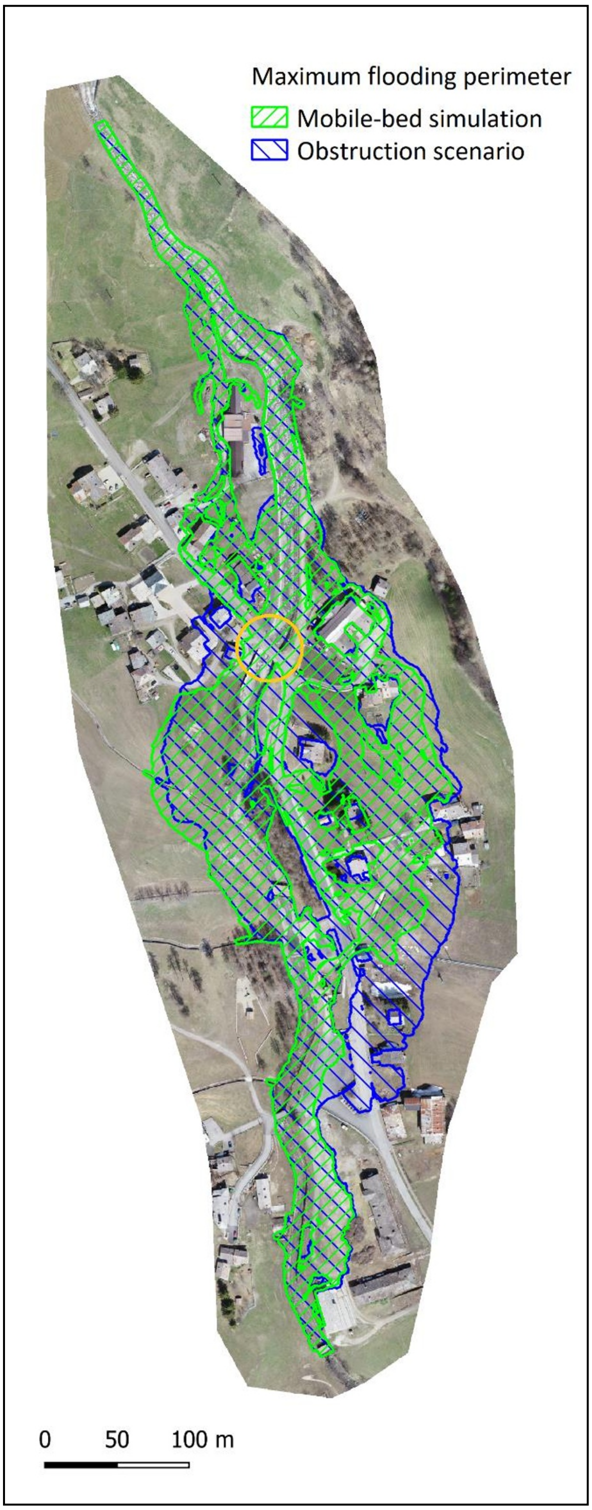

Fig. 4. Comparison of maximum flooding area obtained with the “standard” simulation and the obstruction scenario. The circle highlights the position of the bridge. For the meaning of the simulations refers to the text.

The comparison between the fixed-bed and obstruction scenario is presented in Figure 5, where longitudinal profiles of the river near the bridge are plotted at different instants and for different conditions.

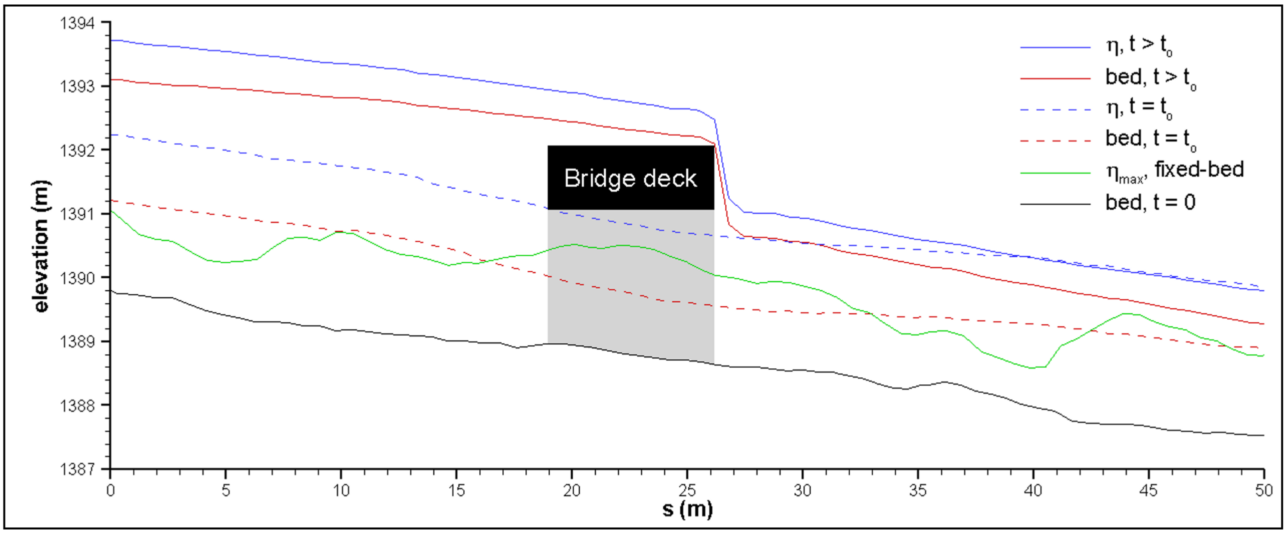

Fig. 5. Longitudinal profile of the river near the bridge. The green line represents the maximum free surface (η) for the fixed-bed simulation; the black line is the bed elevation at the beginning of the simulation; dashed lines represent the bed (red) and free surface (blue) elevations at time t_0 for the mobile-bed simulation; the solid red line represents the bed elevation, while the blue is free surface elevations for a time greater than t_0 in the case of the obstruction scenario simulation. The black and grey areas indicate the zone that is filled for the second simulation of the obstruction scenario simulation.

It is evident that with the fixed-bed simulation the mixture flows under the bridge without interferences (green line). Using a mobile-bed approach, instead, the bed elevation starts to increase causing, at $t=t_0$, the interference between the free surface and the lower side of the bridge deck (blue dashed line for the free surface and red dashed line for bottom elevation). When this happens, the bridge section (the grey and the black area) is closed and the mixture must flow over the deck (blue solid line) producing a conspicuous increase of deposition (solid red line) in the upstream zone and a large overflow (not reported here).

Finally, a comparison between the results of the obstruction scenario with the inundated area that occurred during the August 2017 events (not reported for brevity) was carried on. The results show that even though the hydrological forcing of this event is rather different from that of the synthetic hydrograph with a return period equal to 100 years and the DTM used in the simulations (current state) is somewhat different from the pre-event condition, the extension of the inundated area is reasonably similar.

4 Conclusions

Bridge clogging due to debris-flow events is an important phenomenon that affects mountain areas. Even if preliminary, the results of this work suggest that:

1. The widely used approach of designing and verifying bridge sections by using a fixed-bed water flow model leads to a significant underestimation of the inundated area. This means that the hazard associated with debris flows phenomena is drastically underestimated and a false sense of security can arise among the population.
2. Lacking a rational and systematic theory for debris clogging and pending the development of a better methodology, the simple procedure we have proposed for simulating the bridge clogging scenario seems to be a reasonable and effective approach.
3. The proposed procedure is general, and it can be used also with other numerical models able to tackle the mobile-bed condition and the non-erodible zone.

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References

1. T. Gschnitzer, B. Gems, B. Mazzorana, M. Aufleger, Geomorphology **279**, 128-140 (2017)
2. F. Macchione, M. Lombardo, Water Resour. Res. **57**, e2021WR030485 (2021)
3. G. Spreitzer, J. Tunnicliffe, H. Friedrich, Ecol. Eng. **161**, 106156 (2021)
4. A. Armanini, L. Fraccarollo, G. Rosatti, Comput. Geosci. **35**, 993-1006 (2009)
5. G. Rosatti, D. Zugliani, J. Comput. Phys. **285**, 226-250 (2015)
6. D. Zugliani, G. Rosatti, *A new Osher Riemann solver for shallow water flow over fixed or mobile bed*, in Proceedings of the 4th IAHR Europe Congress, 27-29 July 2016, Liege, Belgium (2016)
7. D. Zugliani, M. Pasqualini, G. Rosatti, *Dynamic transition between fixed- and mobile-bed: mathematical and numerical aspects*, in Proceedings of the EGU General Assembly, 23-28 April 2017, Vienna, Austria (2017)