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Bridges in small basins with intense sediment transport and debris flow

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Abstract

In Italy a significant part of the bridge collapses are due to hydraulic causes. Despite this, the Italian technical construction standards NTC 2018 provide few indications about the design and verification criteria of bridges with respect to river processes.
In 2022, a working group on the "Hydraulic Compatibility of Bridges" (sites.google.com/view/gii-ponti) was set up within the Italian Group of Hydraulics (GII - Gruppo Italiano di Idraulica), with the aim of formulating proposals for good practices and guidelines for assessing the bridge hydraulic compatibility, as a basis for both bridge safety and flood risk analysis. The working subgroup on "small basins" aims to provide analysis tools for small river basins: they have peculiar features, requiring the adoption of appropriate criteria for the analysis of forcing scenarios and safety measures to be implemented for the hydraulic compatibility of river-crossing bridges. Particular attention is devoted to climatic changes that, although gradual, can induce strongly non-linear responses. The present manuscript reviews the current best practice for analyzing the hydrologic response, the

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sediment balance, the flow propagation and the dynamic impact force against bridges in the case of mountain basins, pointing out limitations and possible future developments required in order to develop guidelines for bridge safety and flood hazard assessment.

Keywords: bridge hydraulic compatibility; small river basins; flood risk analysis; sediment transport; debris flow.

1. Introduction

The Italian Group of Hydraulics, GII, established a working group with the objective of formulating best practice proposals and guidelines for bridge hydraulic compatibility assessments, as a basis for both bridge safety and flood risk analysis. This initiative arose from the observation that regulations provide vague guidance on hydraulic design and test criteria for river crossing bridges, although a significant number of bridge collapses are due to hydraulic causes.

A specific working table was created in order to address the methodology for identifying the forcing scenarios and the measures to be implemented in the case of small river basins, which are typically characterized by large slopes, rapid hydrologic response and intense sediment transport, with the possible formation of mudflow and debris flow when intense precipitations occur (Larcher et al. 2022). The above characteristics drive the need to develop specific methods, accounting also for climate change and the consequent progressive increase of extreme meteoric events frequency and intensity (Barnett et al. 2005). These climatic variations, although gradual, can in fact induce non-linear responses (Steffen 2018): when certain rainfall thresholds, which were possibly never or rarely reached in the past, are exceeded, extreme consequences can be triggered (e.g., debris flow and mudflow), exposing the population and the territory to unexpected disasters and calamities.

Debris flows differ from ordinary sediment transport in rivers because of their large sediment volume concentration, which can exceed 30% and even reach 60-70%, and non-Newtonian rheology (Takahashi 1991; Berzi et al. 2010). Moreover, in debris flow the motion of the granular phase is induced directly by gravity and not by the fluid, as in ordinary sediment transport.

Debris flow develop in steep channels if all the following conditions are met: *i*) sufficient availability of sediment (Marchi et al. 2019, Aronica et al. 2012); ii) connectivity of such potential sediment sources with the main channel; iii) slopes large enough to trigger debris flows and allow their downstream propagation (Steger et al. 2022). In addition, debris flow can originate and propagate also at milder slopes when water and sediments are suddenly released due to the failure of natural or artificial barriers. Debris flows often incorporate also large boulders and a considerable fraction of woody material, which enhances the clogging occurrence at bridges.

2. Methods

2.1. Hydrological response of small basins

An accurate liquid hydrography analysis is the first, fundamental step of the methodology for verifying the hydrogeological risk and safety strategies for bridges built in small river basins. Hydrological models receive meteorological data as input, perform calculations and output the liquid discharge.

Meteorological information, such as precipitation and temperature, represents therefore a key factor for hydrograph calculation: the rapid hydrological response of small mountain basins requires accurate short-interval precipitation data, possibly at sub-hourly scale (e.g. Mazzoglio et al. 2020; Martinengo et al. 2021), a fine-spatial resolution (e.g. Crosta et al. 2001, Aronica et al. 2012) and, at the same time, taking into account the effects of the global temperatures increase (e.g. Allamano et al. 2009). Finally, signals of trends on rainfall extremes (e.g. Libertino et al. 2019) require special attention for their possible effect on the increase of discharge extremes, as well as localized climatic phenomena (e.g. Hirschberg et al. 2021).

A critical aspect in obtaining accurate weather data with a fine spatial and time resolution is represented by the scarcity of weather stations, which needs to be overcome with different strategies, including regional climate model simulations, radar and satellite data, and local weather predictions.

2.2. Sediment balance

A good understanding of the basin system is necessary in order to quantify the sediment volumes potentially entrained by a debris flow. Firstly, potential sediment source areas have to be mapped and their thickness assessed. High-resolution topography and field surveys, ideally complemented by geophysical measurements, are crucial for this step. Secondly, the actual degree of connectivity of such potential sediment volumes with the main channel has to be determined. If adequate data and computing resources are available, typically for relatively small spatial scales (Ivanov et al. 2020), numerical models can be applied (e.g. Brambilla et al. 2020; Gatti et al. 2020). However, for large river basins or regional studies, or simply when the necessary data for carrying out meaningful simulations are missing, a simpler, geomorphometry-based approach, which is mostly built on high-resolution DEMs coupled to a solid statistical modelling, is better suited (e.g. Steger et al. 2022). A similar approach can be employed, coupled with an accurate GIS-based forest inventory, for the evaluation of entrained and transported woody debris (e.g. Comiti et al. 2016).

2.3. Debris flows discharge

The theoretical, maximum possible debris flow discharge, Q_{df}, can be calculated using a hydraulic method (e.g. Takahashi 1991) when the liquid discharge, Q, and the sediment concentration at rest, C_0, are given. This theoretical value, Q_{df}, will be effectively reached under the condition that the volume of available sediment is sufficiently large (see chapter 2.2).

$$Q_{df} = Q \frac{C_0}{C_0 - C} \quad (1)$$

In equation (1), the debris flow concentration, C, is assumed to coincide with that of incipient motion in saturated conditions,

$$C = \frac{\tan\alpha}{\Delta(\tan\phi - \tan\alpha)}, \quad (2)$$

where α represents the channel slope angle, ϕ the sediment friction angle and $\Delta = (\rho_s - \rho)/\rho$ the relative buoyant density of sediments (Armanini et al. 2005). In case of topographic variations, the sediment concentration, and therefore the debris flow discharge, can vary significantly in space and time, developing erosion and deposition zones that can be predicted correctly only through the application of appropriate two-phase mathematical models (see chapter Errore. L'origine riferimento non è stata trovata.). Moreover, the flow properties can be affected by the presence of sediments of multiple sizes (e.g. Larcher & Jenkins 2019), with larger boulders typically more concentrated at the debris flow front and on the sides.

The rapid hydrologic response of small basins is also reflected in a very short duration of debris flow hydrographs, with very steep rising limbs and a fast-declining recession phase (Coviello et al. 2021).

2.4. Debris flow propagation

Although debris flow is composed of a solid and of a liquid phase, the mixture as a whole behaves like a non-Newtonian fluid, with features somewhat different from pure water. The flow can be modelled with a system of differential equations for the mass and momentum balance of the liquid and of the solid phase, complemented by a suitable number of closure equations (Sansone et al. 2021). For this purpose, the shallow flow assumption is commonly employed (e.g. Armanini et al. 2009), thus modelling the system in two dimensions, neglecting the vertical component of the flow velocity and assuming a hydrostatic pressure distribution.

Several simplified versions of the two-phase model are present in the literature, as well as monophase models that can describe properly the behavior of mudflows (e.g. O'Brien et al. 1993), but are not suitable for capturing erosion and deposition processes typical of debris flow (Rosatti and Zugliani 2015). Another key aspect in modelling debris flow is the capability of the model to cope with flows over both mobile and fixed bed, which is not possible using monophase models.

Most of the commercial models use the monophase approach over fixed bed, eventually with potential entrainment (Hussin et al. 2012).

2.5. Impact force acting on bridge structure

Debris flows and mudflows typically propagate in steep streams at very large velocities, sometimes exceeding 10 m/s, with a mixture density that can double that of water. As a consequence, their impact force against bridge piers and deck can be destructive (see Fig. 1) and should not be evaluated with the same methods used for lowland rivers.

Fig. 1. Collapsed bridge after a debris flow event on the Rio di Tel (Parcines, BZ). Courtesy of *Agenzia per la Protezione Civile della Provincia Autonoma di Bolzano*.

The impact force of the debris flow or of the mudflow can instead be calculated through a momentum balance applied to a fixed control volume that includes the incident front a few instants after the impact against the bridge (Armanini et al. 2020), considering the mixture as an homogeneous flow. The resulting impact force per unit width, S, against the structure can be expressed as a function of the debris flow density, ρ_{df}, of the gravitational acceleration, g, and of the debris flow front velocity, u, and depth, h:

$$S = \frac{1}{2}\rho_{df} g h^2 \cos\alpha + \rho_{df} u^2 h \quad (3)$$

In some cases, however, the impact of a single, large boulder against a part of the structure can determine a force exceeding the prediction given by equation (3). Therefore, it is appropriate to estimate the size of the largest boulders through field analysis and evaluate their impact force as if they were moving with the same velocity of the debris flow front. The latter can be estimated in first approximation with uniform flow formulas (e.g. Armanini et al. 2005) or, preferably, with mathematical models (see chapter 2.4). The presence of a deformable protection in front of the bridge allows reducing significantly the impact force of single boulders, because it is inversely proportional to their arrest time. The maximum value between the force of a single boulder and the force resulting from equation (3) should then be assumed as design impact force. Field observations on the Gadria torrent (BZ) show that the impact force of a single, large boulder can be up to 5 times larger than the dynamic impact force generated by a homogeneous debris flow front (Hübl, 2022) if deformable protections are not used. Moreover, the dynamic impact force of a debris flow against a structure can in some cases exceed by one order of magnitude the static force.

In the case of mudflow, characterized by highly concentrated mixtures of water and fine sediments, the peak value of the impact force can be assumed equal to the asymptotic value of the final hydrostatic condition. The conditions in which it is possible this assumption depend on the fluid rheological characteristics and the geometrical parameters governing the phenomenon (Di Cristo et al. 2022).

2.6. Bridge clogging

A critical element for the hydraulic safety of steep torrents is represented by the presence of bridges: abutments and piers may generate a narrowing of the flow section, inducing sediment deposition upstream of the bridge. Also a bed slope reduction near the bridge can produce similar effects. Consequently, it is not so rare that the free surface of the debris flow reaches the lower level of the bridge deck (see Fig. 2), leading in some cases to a complete section obstruction. Despite the importance of this phenomenon, to the best of our knowledge a comprehensive experimental study is not available.

Fig. 2. Obstructed bridge after a debris flow event on the Rio di Croda Rossa (Anterselva, BZ). Courtesy of *Agenzia per la Protezione Civile della Provincia Autonoma di Bolzano*.

A practical approach for hazard assessment can be proposed using a mathematical model suitable for describing bed changes due to deposition (therefore excluding monophase models), as well as flow over a non-erodible bed, (when the bridge is overtopped). When the free-surface level of the debris flow reaches the lower level of the deck for at least some minutes, the bridge can be assumed as obstructed and, from that moment on, the bridge section can be considered as a rigid wall. In this way the numerical simulation is split into a pre-clogging and a post-clogging phase. A back-analysis of a real event (Amaddii et al. 2022) shows the reliability of the estimate of the clogging time using this approach, as well as the importance of the bridge clogging simulation when producing hazard maps (Zugliani et al. 2022).

3. Conclusion and discussion

Several significant aspects emerged from the analysis carried out by the working group of Italian Group of Hydraulics on debris and mud flow phenomena in small basins: *i*) investigations in analyzing these basins should be performed using distinct methodologies as compared to lowland streams; *ii*) debris and mudflows have to be clearly distinguished from ordinary sediment transport phenomena and also landslides, and should therefore be treated accordingly; *iii*) the use of alternative rainfall data sources (e.g. radar) might improve spatial and temporal resolution of the phenomena as there is a lack of sub-hourly rainfall data; *iv*) the available hydrometric data are extremely limited; *v*) the debris flow discharge calculated with hydraulic models will exceed the effectively observed one in the case of a scarce sediment availability; *vi*) debris and mudflows can cause significant bed elevation variations in a very short time, which can be predicted properly only with two-phase mathematical models, possibly capable to analyze transitions between erodible-bed and fixed-bed conditions; *vii*) the dynamic impact force produced by mass-transport phenomena against bridge piers and decks can in some cases exceed by one order of magnitude the static one.

The considerations above may provide a starting point not only for the drafting of guidelines, but also for the development of new research activities.

References

Allamano P., Claps P., Laio F., 2009a. An analytical model of the effects of catchment elevation on the flood frequency distribution, Water Resour. Res., 45, W01402, doi:10.1029/2007WR006658.

Allamano, P., Claps P., and Laio F., 2009b. Global warming increases flood risk in mountainous areas, Geophys. Res. Lett., 36, L24404, doi:10.1029/2009GL041395.

Amaddii, M., Rosatti, G., Zugliani, D., Marzini, L., Disperati, L., 2022. Back-Analysis of the Abbadia San Salvatore (Mt. Amiata, Italy) Debris Flow of 27-28 July 2019: An Integrated Multidisciplinary Approach to a Challenging Case Study. Geosciences 12(10), 385.

Armanini, A., Fraccarollo, L., Larcher, M., 2005. Debris Flow. Encyclopedia of Hydrological Sci-ences, M. G. Anderson Editor. John Wiley & Sons, Chapter 142, Vol. 4(12), 2173-2186.

Armanini, A., Fraccarollo, F., Rosatti, G., 2009. Two-dimensional simulation of debris flows in erodible channels. Computers & Geosciences, 35(5), 993-1006.

Armanini, A., Rossi, G., Larcher, M., 2020. Dynamic impact of a water and sediments surge against a rigid wall. Journal of Hydraulic Research 58(2), 314-325.

Aronica G.T., Brigandì G., Morey N., 2012. Flash floods and debris flow in the city area of Messina, North-East part of Sicily, Italy in October 2009: the case of the Giampilieri catchment, Natural Hazard and Earth System Sciences 12(5), 1295-1309.

Aronica G.T., Cascone E., Brigandì G., Biondi G., Randazzo G., Lanza S., 2012. Assessment and mapping of debris flow risk in a small catchment in Eastern Sicily through integrated numerical simulations and GIS, Journal of Physics and Chemistry of Earth 49, 52–63.

Barnett, T., Adam, J. & Lettenmaier, D., 2005. Potential impacts of a warming climate on water availability in snow- dominated regions. Nature 438, 303-309.

Berzi, D., Jenkins, J.T., Larcher, M., 2010. Debris flow: recent advances in experiments and modeling. Advances in Geophysics, 52, 103-138.

Brambilla D., Papini, M., Ivanov V., Bonaventura L., Abbate A., Longoni L., 2020. Sediment Yield in Mountain Basins, Analysis, and Management: The SMART-SED Project. In: De Maio, M., Tiwari, A. (eds) Applied Geology. Springer, Cham. Applied Geology, 43–59.

Carrara, A., Crosta, G., & Frattini, P., 2008. Comparing models of debris-flow susceptibility in the alpine environment. Geomorphology 94(3-4), 353-378.

Comiti, F., Lucía, A., & Rickenmann, D., 2016. Large wood recruitment and transport during large floods: a review. Geomorphology 269, 23-39.

Coviello, V., Theule J.I., Crema, S., Arattano, M., Comiti, F., Cavalli, M., Lucla, A., Macconi, P., Marchi, L., 2021. Combining Instrumental Monitoring and High-Resolution Topography for Estimating Sediment Yield in a Debris-Flow Catchment. Environmental & Engineering Geoscience 27 (1): 95–111.

Crosta, G. B., & Frattini, P., 2001. Rainfall thresholds for triggering soil slips and de-bris flow. In Proceeding of 2nd EGS Plinius Conference on Mediterranean Storms, Siena, Vol. 1, pp. 463-487.

Di Cristo, C., Fecarotta, O., Iervolino, M., Vacca, A., 2022. Impact dynamics of mud flow against rigid walls. Journal of Hydrology 612 (Part B).

Hirschberg, J., Fatichi, S., Bennett, G. L., McArdell, B. W., Peleg, N., Lane, S. N., ... & Molnar, P., 2021. Climate change impacts on sediment yield and debris-flow activity in an alpine catch-ment. Journal of Geophysical Research: Earth Surface 126(1).

Gatti, F., Menafoglio, A., Togni, N., Bonaventura, L., Brambilla, D., Papini, M., Longoni, L., 2020. A novel downscaling procedure for compositional data in the Aitchison geometry with application to soil texture data. Stochastic Environmental Research and Risk Assessment.

Hübl, H., 2022. Personal communication.

Hussin, H.Y., Quan Luna, B., Van Westen, C.J., Christen, M., Malet, J.-P., Van Asch, Th.W.J., 2012. Parameterization of a numerical 2-D debris flow model with entrainment: a case study of the Fau-con catchment, Southern French Alps. Natural Hazards and Earth System Science 12(10), 3075-3090.

Ivanov, V., Radice, A., Papini, M., Longoni, L., 2020. Event-scale pebble mobility observed by RFID tracking in a pre-Alpine stream: a field laboratory. Earth Surface Processes and Landforms 45 (3), 535-547.

Larcher, M. Aronica, G.T., Ballio, F., Claps, P., Comiti, F., Di Cristo, C., Lanzoni, S., Longoni, L., Menapace, A., Papini, M., Rosatti, G., Termini, D., Vacca, A., Zugliani, D., 2022. Ponti in piccoli bacini con elevato trasporto di sedimenti, in "*ICIRBM-2022, Proceedings of the 43th Italian Conference on Integrated River Basin Management. Tecniche per la Difesa dell'Inquinamento*", Frega G. and Macchione F. Editors, Volume 43, EdiBios, Cosenza, 371-380. ISBN: 978-88-97181-86-6, ISSN 2282-5517.

Larcher, M., Jenkins, J.T., 2019. The influence of granular segregation on gravity-driven particle-fluid flows. Advances in Water Resources 129, 365-372.

Libertino, A. D. Ganora, Claps, P., 2019. Evidence for increasing rainfall extremes remains elusive at large spatial scales: the case of Italy. Geophysical Research Letters 46(13), 7437-7446.

Marchi, L., Brunetti, M. T., Cavalli, M., and Crema, S., 2019. Debris-flow volumes in northeastern Italy: Relationship with drainage area and size probability. Earth Surf. Process. Landforms 44: 933– 943.

Martinengo, M., Zugliani, D., & Rosatti, G., 2021. Uncertainty analysis of a rainfall threshold estimate for stony debris flow based on the backward dynamical approach. Natural Hazards and Earth System Sciences 21(6), 1769-1784.

Mazzoglio, P.; Butera, I.; Claps, P., 2020. I2-RED: A Massive Update and Quality Control of the Italian Annual Extreme Rainfall Dataset. Water 12, 3308, DOI:/10.3390/w12123308.

O'Brien, J.S., Julien, P.Y., Fullerton, W.T., 1993. Two Dimensional Water Flood and Mudflow Simulation. Journal of Hydraulic Engineering 119(2), 244-261.

Rosatti, G., Zugliani, D., 2015. Modelling the transition between fixed and mobile bed conditions in two-phase free-surface flows: The Composite Riemann Problem and its numerical solution. Journal of Computational Physics, 285, 226-250.

Sansone, S., Zugliani, D., Rosatti, G., 2021. A mathematical framework for modelling rock-ice avalanches. Journal of Fluid mechanics 919, A8.

Steffen W. et al., 2018. Trajectories of the Earth System in the Anthropocene. PNAS - Proceedings of the National Academy of Sciences of the United States of America 115 (33), 8252-8259.

Steger, S., Scorpio, V., Comiti, F., Cavalli, M., 2022. Data-driven modelling of joint debris flow release susceptibility and connectivity. Earth Surface Processes and Landforms 47, 2740-2764.

Takahashi T., 1991. Debris Flow, IAHR Monograph, A. A. Balkema: Rotterdam.

Zugliani, D., Rosatti, G., Martinengo, M., Ataieyan, A., 2022. A practical approach to bridge obstruction scenario simulations in debris flow hazard mapping. Proceeding of the XXXVIII Convegno Nazionale di Idraulica e Costruzioni Idrauliche. 4-7 settembre 2022, Reggio Calabria.