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Risk Assessment of Transport Linear Infrastructures to Debris Flow

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Abstract. For the assessment of debris flow risk, it is essential to consider not only the triggering and propagation stages but also to perform analyses of its effects and consequences. The study aims at developing a procedure based on a quantitative risk assessments able to estimate the different levels of risk with reference to transport linear infrastructures. This includes numerical modelling for debris flows to determine the zones where the elements at risk could suffer an impact. A detailed comparison between the performances of two different approaches to debris flow modelling was carried out. In particular, the results of a mono-phase Bingham model (FLO-2D) and that of a single-phase model (RASH-3D) with reference to the Enna area (Sicily). The results can be applied for the risk calculations. The purpose is to define a priority of intervention for the identification of the infrastructures exposed at risk, leading to the choice of safety measures.

1 Introduction

Linear transport infrastructure systems are often subjected to landslide and debris flow events. Hazard maps, as well as, direct risk estimation play an important role to mitigate related effects.

Landslides have also a strong impact on the road and railway systems, creating the need to define criteria for management and mitigation of risk through landslide zoning correlated with transport infrastructure network [1-2]. In particular, the risk evaluation requires analysis of the spatial and temporal probabilities that a given element is hit by a landslide of a particular type and magnitude [3], the estimation of rainfall and triggering factors, the dynamic of the event, the area of propagation, etc.

The destructive potential of a landslide mainly depends on velocity. As a consequence "rapid landslides", such as debris flows and rock-slide debris avalanches, are the most dangerous for transport infrastructure systems.

The state of the art of prevention is performed thanks to development of hazard maps, built with the data taken from historical records, numerical simulations and small and/or medium scale physical modelling. With this aim, several numerical models have been developed for simulating landslide propagation and run-out [4-7].

The choice of the rheology is a fundamental aspect of numerical simulation. To derive useful information for the calibration of model parameters, the back-analysis of a debris flows occurred in Enna (Italy), is reported. In order to understand the real behaviour of the propagation of a debris flow on a large scale, a real debris flow event was analysed by means of two different models: the FLO-2D [8-9] and the RASH-3D [10]. Comparison among obtained results underlines that the validation of a rheology requires not only a good agreement between the numerical simulation results and the run out area boundaries but also in term of depth distribution of the mass.

2 Case study: the 2014 Enna debris flow

During the night between the 1st and the 2nd of February 2014 a heavy rainfall struck the city of Enna (Italy), causing several damages. Very large amount of soil deposited on the road (Figure 1), providing the interruption of the infrastructure connecting Enna at the highway "A19 Palermo-Catania". About 150 mm of rainfall in less of 1 hour characterized the event. This area is characterized by a morphology with high hill slope angles (within a range of 30 ÷ 60°) and with catchment areas of small extension (about 0.158 km^2).

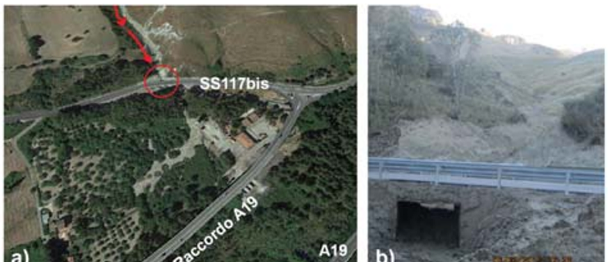


Fig. 1. Flow mass in the deposition area close to the main road ("SS117bis"): a) plan view and b) detail of the connecting with the highway.

3 Numerical modelling and back analysis procedures

In order to understand the behaviour of their propagation on a large scale, the mentioned real debris flow event, was analyzed by means of two different models.

The first one is FLO-2D code, which is based on a mono-phasic Bingham scheme, modelled through the quadratic rheological law developed by O'Brien and Julien and, the second is RASH3D code based on a single-phase continuum mechanics approach and on depth-averaged St. Venant equations.

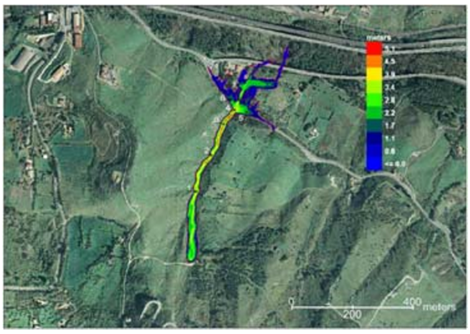
The presented numerical analyses, in particular, intended to investigate: (i) the capability of the codes to simulate the dynamics of the debris flow (propagation and deposition) and, (ii) the influence of the associated calibrated rheological parameters on the numerical results.

3.1 Results of FLO-2D numerical simulations

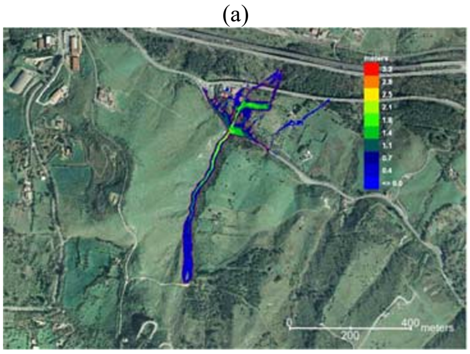
3.1.1 Enna debris flow

In order to model the debris flows occurred in Enna three principal data sets are needed: a digital terrain model (DTM), hydrological data, and rheological properties of the sediment - water mixture. For the construction of the DTM a grid system with cell size 2.0 m x 2.0 m was implemented by FLO-2D model. The hydrological input is applied at the upstream section of the basin where the triggering was observed. The discharge rate value of the debris flows for the basin has been calculated.

A reconstruction of the inundated area was obtained as output of the simulations performed by the FLO-2D code (Figure 2).



(a)



(b)

Fig. 2 Scenarios simulated with FLO-2D code for Enna debris flow: (a) maximum flow depth, (b) final flow depth.

The computed maximum flow depths during the event are presented in Figure 4a. The highest predicted flow depth is about 4.0 m. Figure 4b represents the final flow depths. The highest value of the predicted final flow depth is about 1.4 m. It has been found that the maximum velocities are registered in correspondence of the upper part of the basins and the slope is the highest, with values ranging from 1 to 2 m/s.

The predicted values are, in general, in good agreement with those observed. This is supported by the comparison between the computed volume and the measurement of the deposited sediment after the event resulting from the surveys of the Regional Civil Protection.

3.2 Results of RASH-3D numerical simulations

To RASH-3D model was applied referring to the event occurred on 1-2 February 2014. The trigger volume to be used as input data in the numerical analysis of propagation via the model RASH-3D is of about 1400 m^3 (Figure 3), according to the on-site survey reported by [11].

Numerical simulations have been carried on choosing the Voellmy rheology and the values of the friction coefficient μ and the turbulence coefficient ξ reported in Table 1.

The results obtained by RASH-3D model are summarized in terms of final flow depth (Figure 4), representing the maximum flow height in the deposition area, and the maximum flow velocity (Figure 4).

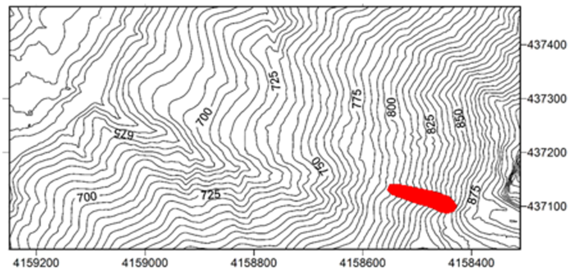
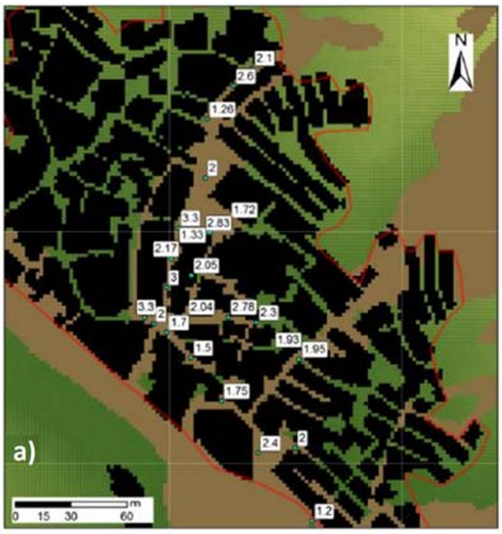


Fig. 3 Comparison between: a) measured [12] and b) computed maximum flow depth



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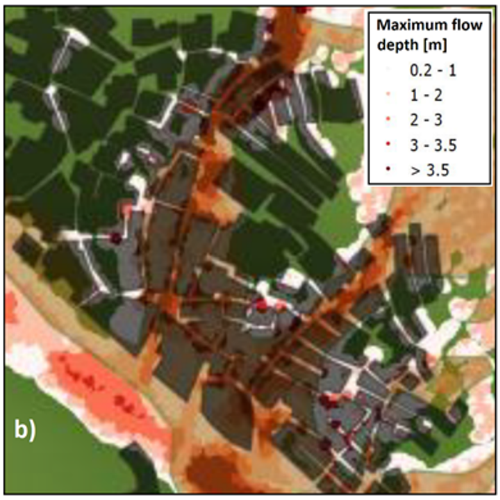

Fig. 4 Comparison between: a) measured [12] and b) computed maximum flow depth

Table 1. Rheological parameters used in numerical analyses carried out by RASH-3D code (Enna event).

Analysis	1	2	3	4
Friction coefficient μ [-]	0.1	0.1	0.05	0.05
Turbulence coefficient ξ [m/s^2]	500	1000	500	2000

In particular, the results reported in Figure 5 and 6 correspond to the best-fit between predicted and observed values both as concern the depth than the velocity of the flow mass, especially in the deposition area close to the main road SS117bis interrupted due to the debris flow, connecting the city of Enna at the highway A19.

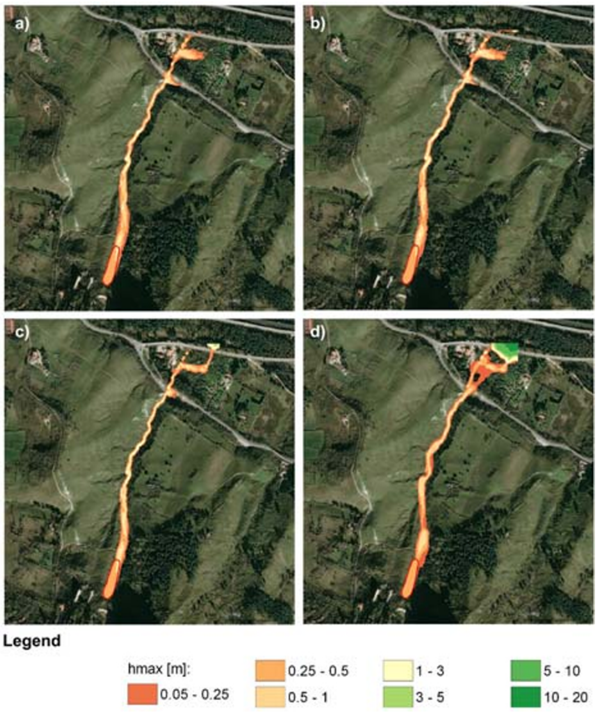

Fig. 5 Maximum debris flow height simulated with the RASH-3D code: (a) analysis 1, (b) analysis 2, (c) analysis 3 and d) analysis 4

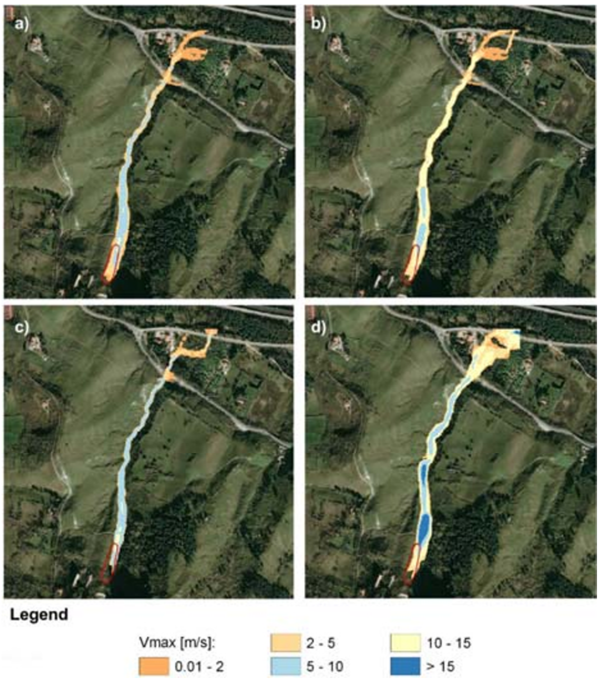

Fig. 6 Maximum flow velocity simulated with the RASH-3D code: (a) analysis 1, (b) analysis 2, (c) analysis 3 and d) analysis 4.

4 Debris Flow Susceptibility and Estimation of Direct Risk

The results obtained from numerical modelling of the propagation phase of debris flows can be used to draw the debris flow susceptibility maps and/or to represent a preliminary level of landslide susceptibility zoning of a study area. In particular, the path, the travel distance and the velocity of flowing mass are useful to evaluate also the consequences in terms of effects of the expected events.

In the last few years, quantitative risk assessments (QRA) has become an essential tool for management of landslide hazard and for planning risk mitigation measures at a detailed scale.

According to [13], the framework for the use ofQRA for landslides and engineered slopes comprises three main components, i.e., risk analysis, risk assessment and risk management. Risk analysis includes hazard and consequence analyses. Risk estimation is the final step of the risk analysis and essentially consists in the risk calculation through a probabilistic equation.

The second step of the procedure is represented by the quantitative risk assessments (QRA), relating flow volume to damage probabilities.

Following the procedure proposed by [13], suitably modified, the risk estimation can be related to the annual probability $P^i_{(LOL)}$ that a particular person may lose his/her life calculated as a function of: the frequency of the landslide events of a given i-magnitude; the probability of the landslide reaching the element at risk; the temporal spatial probability of the element at risk; the vulnerability of the element to the landslide event.

The procedure, described in detail in [1], has been applied to the case of the debris flow event occurred on February 2014 close to the city of Enna (Italy).

The quantitative risk assessment involved the estimation of the annual probability $P^i_{(LOL)}$, by assuming a return period (T=10 years) equal to the period of the triggering rainfall.

Assuming that an infrastructure has an unacceptable state, and no longer compatible with social needs when the probability of loss of human life is higher than the threshold value of 10^{-4} (Table 2), a "Severity Index" (Is) can be defined as an indicator of the level of weakness of the infrastructure, connected to the risk to which users are exposed for a landslide occurrence. Thus the values of the Severity Index (Is) reported in Table 2 can be suggested to evaluate the different level of risk.

Table 2. Severity Index values.

Level	$P_{(LOL)}$	I_S
Very High	$P_{(LOL)} > 1 \cdot 10^{-3}$/annum	50
High	$1 \cdot 10^{-4} < P_{(LOL)} < 1 \cdot 10^{-3}$ /annum	40
Moderate	$1 \cdot 10^{-5} < P_{(LOL)} < 1 \cdot 10^{-4}$ /annum	30
Low	$1 \cdot 10^{-6} < P_{(LOL)} < 1 \cdot 10^{-5}$ /annum	20
Very Low	$P_{(LOL)} < 1 \cdot 10^{-6}$/annum	10

5 Concluding remarks

This study aims at developing numerical modelling for debris flows able to calculate physical outputs (extension, depths, velocities) and to determine the zones where the elements at risk could suffer an impact with reference to the transport linear infrastructures.

These results can then be applied to risk calculations, reproducing in thematic maps by different risk levels the distribution of the flow mass on the propagation path, its intensity, and the zone where the elements will experience an impact.

The following step is the risk estimation adopting, for example, a procedure based on a quantitative risk assessments. In fact, a quantifiable integrated approach of both hazard and vulnerability is becoming a required practice in risk reduction management.

In this paper a Severity Index has been defined as an indicator of the level of weakness of the infrastructure, and values for this index have been suggested to evaluate the different level of risk.

The final purpose is to define a priority of intervention for the identification of the ex-posed infrastructures at risk (accurate and objective), leading to the choice of safety measures in view of an effective and sustainable infrastructure planning and management.

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