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Multi-temporal LiDAR-DTMs as a tool for modelling a complex landslide: a case study in the Rotolon catchment (eastern Italian Alps)

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Abstract. The geomorphological change detection through the comparison of repeated topographic surveys is a recent approach that benefits greatly from the latest developments in topographical data acquisition techniques. Among them, airborne LiDAR makes the monitoring of geomorphological changes a more reliable and accurate approach for natural hazard and risk management. In this study, two LiDAR digital terrain models (DTMs) (2 m resolution) were acquired just before and after a complex 340 000 m^3 landslide event (4 November 2010) that generated a debris flow in the channel of the Rotolon catchment (eastern Italian Alps). The analysis of these data was used to set up the initial condition for the application of a dynamic model.

The comparison between the pre- and post-event DTMs allowed us to identify erosion and depositional areas and the volume of the landslide. The knowledge of the phenomenon dynamics was the base of a sound back analysis of the event with the 3-D numerical model DAN3D. This particular code was selected for its capability to modify the rheology and the parameters of the moving mass during run-out, as actually observed along the path of the 2010 debris flow.

Nowadays some portions of Mt. Rotolon flank are still moving and show signs of detachment. The same soil parameters used in the back-analysis model could be used to simulate the run-out for possible future landslides, allowing us to generate reliable risk scenarios useful for awareness of civil defense and strategy of emergency plans.

1 Introduction

Recent improvements in topographical data acquisition techniques and software allow us to derive high-resolution digital terrain models (DTMs) and develop new methodologies for analyzing earth surface processes (e.g. McKean and Roering, 2004; Lane et al., 2004; Lashermes et al., 2007; Iwahashi et al., 2012; Cavalli et al., 2013; Tarolli, 2014). Among these techniques, light detection and ranging (LiDAR) is probably the most important technological innovation for geomorphic research (Roering et al., 2013) and, in the last years, its applications in geomorphology and natural hazard fields have significantly increased (Notebaert et al., 2009; Jaboyedoff et al., 2012; Roering et al., 2013). In particular, comparisons of LiDAR-derived DTMs obtained from successive surveys make it possible to produce DEM of differences (DoD) maps, which are a valuable tool to interpret the evolution of geomorphological processes and to quantitatively assess morphological changes due to erosion and deposition on rivers (Lane et al., 2003; Wheaton et al., 2010; Picco et al., 2013;) and in case of debris flows (Scheidl et al., 2008; Theule et al., 2012; Blasone et al., 2014) and landslides (Burns et al., 2010; DeLong et al., 2012).

Another tool broadly used to investigate the dynamics of geomorphological processes is numerical modelling (Hungr et al., 2005, Rickenmann, 2005). Dynamic run-out models can simulate the propagation of material after initial failure and delineate the zones where elements at risk will suffer an impact with a certain level of intensity (Quan Luna et al., 2011). The results of these models are used as input for vulnerability and risk assessments (van Westen et al., 2006). However, numerical models rely on back analysis for validation and the accuracy of results is still not optimal. An important feature of run-out models is the possibility to perform forward analyses (Bossi et al., 2013) and forecast changes in hazards (Crosta et al., 2006). Dynamic computer models have the potential to simulate geomorphological processes with an acceptable degree of accuracy. Once this is achieved, a range of potential hazard scenarios can be analyzed and the results can be used to inform local authorities and the population in order to respond to these hazards and plan the reduction of associated risks (Quan Luna et al., 2014). To model properly the run-out pattern of the flow material during its downslope movement, detailed topographic information from the sliding track and the source zone is needed. Formerly, DTMs for landslide investigation were realized through GPS surveys (Marcato et al., 2006) or derived from contour lines and photogrammetry (Sosio et al., 2008). Nowadays, an improvement in the precision of the DTMs can be expected by using laser scanning techniques such as LiDAR. This will avoid the problem of the lack of accuracy of the DTMs and the stochastic changes in topography during the run-out process (van Asch et al., 2007). In this paper we report the use of DoD maps as a base to calibrate a 3-D model, using the numerical code DAN3D (McDougall and Hungr, 2004), of a large debris flow event that occurred on 4 November 2010 in the eastern Italian Alps.

2 Study area

The Rotolon catchment is located in north-eastern Italy (Veneto region, Italy) and covers an area of 5 km^2 (Fig. 1). The valley stretches along an s-shape from 1930 down to 590 m a.s.l., where the touristic village of Recoaro Terme is located. The basin is bordered by mountains made of sedimentary rocks Triassic in age (from Scythian to Rhaetian) such as dolomite, limestone, sandstones, marls and gypsum. These lithotypes show evident signs of weathering and are affected by joints and fractures. Mainly rhyolite but also breccia and tuff are present, while igneous rocks rarely appear.

Thick deposits cover the upper part of the basin. Some of the deposits originate from rock falls detached from the dolomitic and calcareous formation and others from the underlying altered strata of clayey marls. Steep slopes characterize these deposits, thus predisposing the sediments to mass movement events (Altieri et al., 1994).

The instability phenomena occurring in the Rotolon catchment are linked with the presence of a large deep-seated gravitational slope deformation with a volume of several million cubic metres. The type of movements in the upper part are various: falls, topples and rotational slides that sometimes evolve into debris flow along the Rotolon stream. The vulnerable elements in the catchment are two villages set beside the channel (namely Turcati and Parlati), two bridges and some road sections, along with the city of Recoaro Terme that is located farther downstream (Fig. 1).

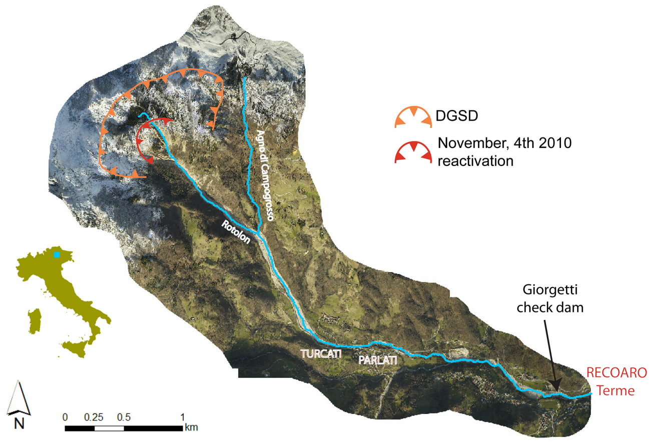

Figure 1. Study area: post-event orthophoto with the main hydrographic network and the landslides crowns highlighted.

Several important debris flow events have been documented in the Rotolon catchment since 1798. In 1985, a large reactivation led to a renewed interest in the phenomenon mainly aimed at the definition of possible mitigation measures. More recently, in 2009, a debris flow threatened the village of Turcati, depositing in the channel a volume of 30 000 m^3 of debris. In the last event, which occurred on 4 November 2010, a mass of 340 000 m^3 detached as a rotational slide from the flanks of Mt. Carega and partially evolved into a debris flow along the main channel. This event produced a channel aggradation of about 3 m near the villages of Turcati and Parlati, causing alarm among the population.

An automatic monitoring network (Frigerio et al., 2014) and an early-warning system (Bossi et al., 2015) have been implemented to mitigate the hazard and protect the exposed population. It was crucial to obtain a reliable numerical reconstruction of the event in order to select the more appropriate material properties to use for defining risk scenarios and to design mitigation measures.

3 Methods

3.1 DoD

Two LiDAR surveys have been conducted in the Rotolon catchment by the Soil Defence Department of the Veneto region. The first was carried out on 21 October 2010 by the regional authority just 13 days before the event, and the second with the same characteristics (i.e. sensors, flight parameters, average point density) was carried out on 23 November. The average point density for both surveys was about 8 pts m^{-2} while the vertical accuracy (root mean square error) of laser data was 0.072 and 0.044 m for the October and

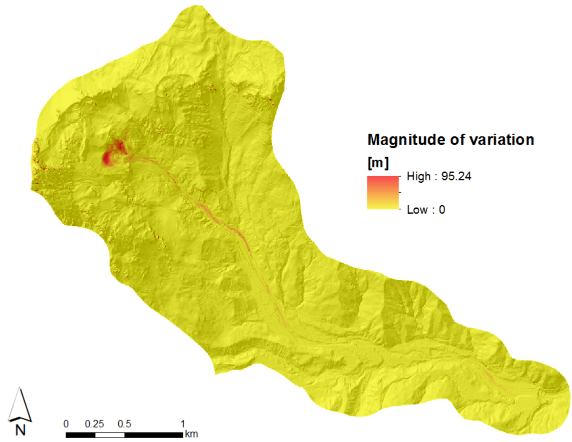

Figure 2. Magnitude of geomorphic change in the Rotolon catchment.

November surveys respectively. The available data consisted of 11 ASCII files already interpolated with a triangulation algorithm and then resampled with linear interpolation on a 2×2 m grid. The 11 files were then converted into ESRI raster format and merged into a single DTM with particular attention to the spatial coherence of the two surveys.

A first comparison between the pre- and post-event DTMs was carried out with the Change Vector Analyses tool implemented in the open-source GIS Whitebox 2.0.2 (http://www.uoguelph.ca/~hydrogeo/Whitebox/). The tool calculates the magnitude (Fig. 2) and the direction of variation (erosion or deposit) by simply subtracting the two topographic surfaces. The resulting rasters show clearly the pattern of the event but are also affected by noise mainly related to the vertical and horizontal accuracy of the LiDAR data (Cavalli and Tarolli, 2011) and to the different results of the filtering process applied to remove LiDAR points belonging to vegetation and buildings in the two raw data sets. Therefore, error propagation was taken into account before quantitative comparisons of sequential DTMs. Both magnitude and direction of variation maps were used to draw a boundary of the area affected by the event in order to focus the DoD analysis where the most evident morphologic variations occurred.

For the DoD analysis, the software GCD 5 (Geomorphic Change Detection, plug-in version for ArcGIS) was used (Wheaton et al., 2010). In the code, several methods to calibrate the DoD calculation are presented. In order to adopt an approach based on the spatially variable assessment of the error, it is necessary to have information about spatially variable DTM quality that is strictly related to the quality of the survey data (Wheaton et al., 2010). Since original LiDAR point clouds were not available, the evaluation of spatial uncertainty in each individual DTM was not possible and a simple minimum level of detection ($_{\mathrm{min}}$LoD; Brasington et al., 2000, Fuller et al., 2003) approach, considering a uniform error, was used. Predicted elevation changes that occurred beneath $_{\mathrm{min}}$LoD were discarded, whereas elevation changes above this limit were treated as real. Brasington et al. (2003) showed the individual errors in the DEMs can be propagated into the DoD as

$$\delta u_{\mathrm{DoD}} = \sqrt{(\delta z_{\mathrm{new}})^2 + (\delta z_{\mathrm{old}})^2}, \tag{1}$$

where δu_{DoD} is the propagated error in the DoD and δz_{new} and δz_{old} are the individual errors of the post- and pre-event DTM respectively. For the analysis, the error in both DTMs was set at 0.2 m, the usual error of airborne LiDAR DTM (Cavalli and Tarolli, 2011), and considered as uniformly distributed.

3.2 Numerical method

The 3-D simulation was performed with the DAN3D software (Hungr and McDougall, 2009) which uses an adapted smoothed particle hydrodynamics approach. The rock mass is discretized into numerous particles that flow forced by topography, based on a selected rheology.

A 3-D modelling code was necessary for modelling the Rotolon landslide as the peculiar course of the river alters the dynamic of the flow, with marked effects of path curvature in the erosion/deposition pattern. Among 3-D codes, DAN3D was chosen because it allows us to modify the rheology of the landslide along the path. The DTM on which the process is simulated could be divided in different zones in which the properties of the flowing mass and the substrate are assigned. This was crucial because the dynamic of the Rotolon landslide was complex and it was necessary, for example, to recreate the fluidification mechanism caused by the inlet of the Agno di Campogrosso (hereafter called Agno), a secondary stream. In fact, the Agno inlet was considered a separation zone between the upper and lower part of the landslide track. Moreover, DAN3D allows us to consider entrainment of material during the process and permits us to select the maximum erosion depth for each zone of the track. The mechanism of entrainment follows an empirical approach based on the parameter E (erosion rate, [m^{-1}]), which represents the increase of the volume of the flowing mass per unit of distance travelled (McDougall and Hungr, 2005).

The modelling of the Rotolon landslide followed a back-analysis procedure. The soil parameters are selected through trial and error on the basis of the DoD data analysis. In DAN3D the input files are a source area file, which represents the initial geometry of the sliding mass, and the topography file. The availability of pre- and post-DTM files allowed us to greatly reduce the uncertainties connected with these data, as the source file was clearly highlighted in the DoD map and the pre-event DTM was an almost no-error topography file. However, in order to reduce the computational time of the simulation, the cells were resampled onto a 5×5 m grid.

4 Results

4.1 DoD analysis

The resulting differential DTM (Fig. 3) was analyzed in order to identify erosion and depositional areas related to the event and to quantify them in terms of volume (Fig. 4). Main results are listed in Table 1.

Results show a sort of balance between deposition and erosion within the catchment with a total erosion of 400 000 m^3. The 2010 event detached a mass of 340 000 m^3 from the main source area in the upper part of the catchment. This mass partially evolved in a debris flow that stretched for 4.5 km, threatening some villages. The total net volume difference of 15 000 m^3 could be considered as bed load transport at the catchment outlet. Nevertheless, it is worth noting the high error associated with the total net volume (i.e. ±51.347).

4.2 The event as described by the DoD

The dynamic of the 2010 event was quite complex due to the morphology of the valley, the type of sediment involved and the amount of detached material (about 340 000 m^3).

Just after the detachment, part of the material (20 000 m^2) stopped against the upper left flank, filling a small depression and not contributing to the flow along the Rotolon stream. The other 320 000 m^3 fell down in a track characterized by a 27° slope, thus acquiring further energy. Moreover, the presence of a bend along the channel caused erosion on the external part of the river bed due to the effect of transversal velocities. This caused two small lateral failure on the left bank. Later on, in a 900 m long and 15° inclined track located upstream Agno di Campogrosso inlet, 186 000 m^3 of material settled. Here the total erosion was 21 000 m^3, leaving 155 000 m^3 of sediment entering the flatter part of the valley.

The DoD analysis shows that from the Agno di Campogrosso inlet the material flowed for another 3 km in a 7° inclined channel, depositing 149 000 m^3 of material. This suggests that there was a modification of the rheology of the flowing mass due to the increase of water content. Data show that the large Giorgetti check dam (Fig. 1), located just upstream of the city of Recoaro Terme, represents the last section along the Rotolon stream in which a significant deposition occurred.

4.3 Modelling

The coupling of frictional and turbulent behaviour allows us to better describe the complex dynamic of the landslide and its long travel distance associated with more than 10 % of entrainment. Therefore, during the calibration process a Voellmy rheology (Voellmy, 1955) was selected for the model:

$$\tau_{zx} = -\left(f\sigma_z + \frac{\rho g v_x^2}{\xi} \right), \quad (2)$$

where f is the friction coefficient ($f = \tan\varphi_b$ with φ_b bulk basal friction angle) and ξ the turbulence parameter. For the upper part a friction coefficient of $f = 0.18$ and a turbulence parameter of $\xi = 200\,m\,s^{-2}$ were selected, whereas $f = 0.05$ and $\xi = 200\,m\,s^{-2}$ were used for the lower part. These are typical parameters for the modelling of a debris flow in alpine environment (Quan Luna et al., 2013). Moreover, an erosion rate of 0.0001 has been imposed, with a maximum erosion depth of 5 m in the upper part of the track.

As the kinematics of the phenomenon in the detachment area was complex, with the left bank movement difficult to simulate with the same code, our model focused on reconstructing the dynamic and deposition pattern along the channel track, and the results show a good correspondence with the DoD data (Fig. 5). Actually, the volume deposited in the upper section was 196 000 m^3, while it was 152 000 m^3 in the lower tract. The errors are therefore 10 000 m^3 upstream from the Agno di Campogrosso inlet and just 3000 m^3 downstream. This is an acceptable accuracy for the modelling of a large landslide. Nevertheless, the deposition pattern is not perfectly reconstructed; the biggest discrepancy is located just after the Agno di Campogrosso inlet. In the real event the fluidification process took some space and time to develop, with a marked transversal dynamic of deposition in the external part of the curve and erosion in the intern, where the clear water would have likely flown. In fact, from the upper track a flow with a fairly high angle of friction arrives. Then, two events simultaneously occur at the bend: the channel slope changes significantly from 15 to 7°, and the water discharge from the Agno di Campogrosso enters in the main channel. The water flow from the Agno di Campogrosso is directed to the internal part of the bend, thereby fluidifying the internal flow and allowing it to maintain momentum to carry more sediments and also to erode. However, the material flowing on the external part of the bend would have undergone a less significant change in the rheology, thereby depositing more quickly due to the change of channel slope and also to the lesser velocities. In the model, contrarily, the modification of the rheology is immediate and this kind of phenomenon is not recreated properly. Therefore, in the map of the deposits derived from the DAN3D simulation, the levee of the deposit downstream from the Agno di Campogrosso inlet is not present. Another smaller difference is located in the channel upstream from the Agno di Campogrosso inlet: even though the deposition is coherent with the DoD for thickness and shape of the deposit, a smearing effect at the border is present with a 20 m buffer outside the DoD deposit contour. Eventually, the material did not reach the Giorgetti dam. This discrepancy may be explained by the time lag (19 days) between the actual event and the post-event LiDAR survey: it is presumable that some sediment transport occurred after the

Table 1. Main results of the DoD analysis.

Attribute	Raw	DoD estimate with threshold	± Error volume	% Error
Areal				
Total area of erosion (m^2)	114.900	91.732		
Total area of deposition (m^2)	180.276	156.656		
Volumetric			± Error volume	% Error
Total volume of erosion (m^2)	404.048	400.890 ±	25.946	6 %
Total volume of deposition (m^2)	387.705	384.551 ±	44.309	12 %
Total volume of difference (m^2)	791.752	785.441 ±	70.255	9 %
Total net volume difference (m^2)	−16.343	−16.339 ±	51.347	314 %
Percentages (by volume)				
Percent erosion	51 %	51 %		
Percent deposition	49 %	49 %		
Percent imbalance (departure from equilibrium)	−1 %	−1 %		

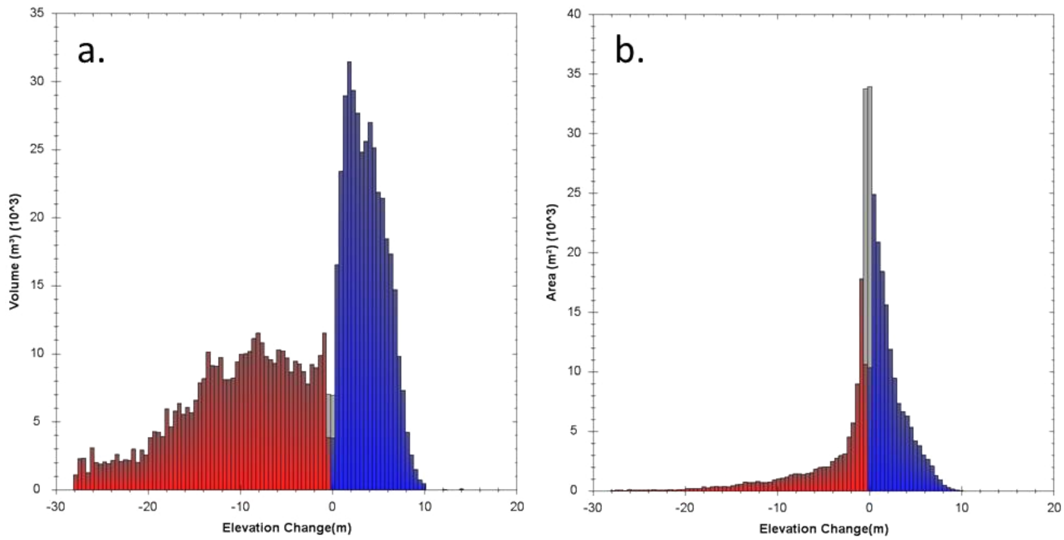

Figure 3. DoD map over shaded relief of the Rotolon catchment.

event and that the deposition front advanced along the channel.

5 Discussion and conclusions

In 2013, Worni et al. stated that the future challenges in numerical modelling of flows are linked to the capability of understanding precisely the dynamic of the phenomena and to the availability of high-resolution DTMs. In this paper we present the use of multi-temporal LiDAR DTMs as a tool to analyze mass movement events in each zone of its track in terms of erosion and deposition, obtaining a clear description of the whole process.

The availability of pre- and post-event DTMs allowed us to enhance the consistency of the numerical model and reconstruct the event of 4 November 2010 in the Rotolon catchment. In Table 2 the main results of the simulation are presented: in the track zone, the erosion values are almost equal and the 13 000 m^3 discrepancy in deposited volume is less than 4 % the total volume of the event.

The DoD approach could thus be used to improve the reliability of back-analysis-based numerical model as the reconstruction of the phenomena usually depends on the definition of a distinct source area, a highly defined pre-event topographic file and a spatially distributed source of information about the erosion/deposition pattern. However, the use of DoD for the analysis of fast-moving flows does not provide the velocities data which are usually obtained through a monitoring system (Arattano and Marchi, 2005). The lack of velocity data is compensated by the information provided

Table 2. Comparison, in terms of volume, of the main results of the DoD analysis and the DAN3D simulation.

Volume [m^3]	DoD			DAN3D			Difference between DoD and DAN3D deposit	
	Erosion	Deposit	Balance	Erosion	Deposit	Balance		
Detachment area								
Main detachment	342 263	1915		332 123*	17 761			
Lateral zone	5227	25 553			1025			
Mass leaving the detachment area			320 022			313 337	6685	2.1 %
Debris-flow track above the Agno inlet	21 746	186 523			196 317		−9794	−5.3 %
Debris-flow track below the Agno inlet	14 275	149 274			152 747		−3473	−2.3 %
Whole debris-flow track	36 021	335 797		35 727	349 064		13 267	4.0 %

* Source area in DAN3D.

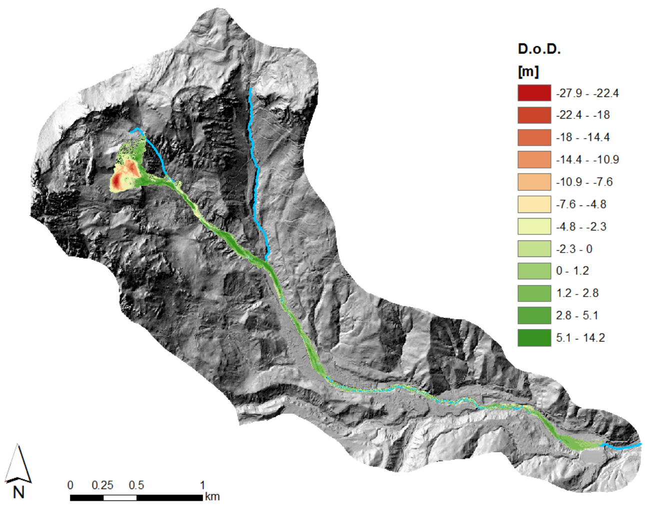

Figure 4. Volumetric and areal distribution of the morphologic variations that occurred between October and November 2010. The deposition is in blue, erosion is in red and the values discarded for the volumetric assessment are in grey.

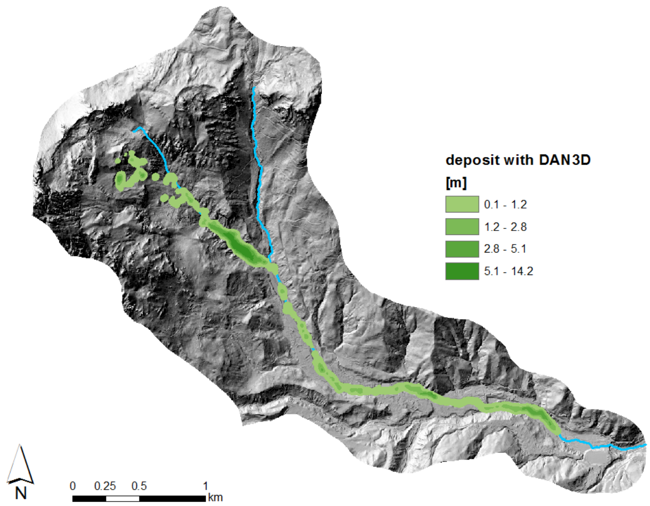

Figure 5. Results of the back-analysis simulation with DAN3D: distribution of the deposits.

by the DoD; nevertheless, it is advisable for future studies to also consider the set up of some instruments like ultrasonic, radar, laser sensors or geophones.

The availability of a pre-event LiDAR survey acquired 13 days before the reactivation was a lucky coincidence and represents the best possible condition. It was possible to simulate the flow over a topographical surface that was not altered by sediment transport processes occurring naturally in the catchment, smaller landslides or human interference. In usual practice, however, requesting a post-event LiDAR survey is relatively easy, while the possibility of obtaining a pre-event DTM depends on the capability of sustaining the economical effort of periodic flights, although their cost has dramatically decreased (Reutebuch et al., 2005). Thus a rational approach could be to investigate the whole territory as measure zero and then concentrate flights for post-event assessment or in periodic surveys on event-prone areas, where a consistent model is necessary to design countermeasure work. The capability of providing a good description of the phenomenon and a reliable numerical model, both describing consistently the whole event from source area to deposition lobes, will also help in evaluating the best options for structural mitigation measures at basin scale. In fact, material properties derived from the back analysis could be used to simulate the run-out of other portions of the landslide that geomorphological analysis indicates are prone to collapse. With this procedure, it is possible to delineate risk scenario even though some errors should be accounted for. In this perspective the integration of DoD analysis with numerical modelling represents a valuable tool for hazard assessment and risk mitigation.

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