Assessing the effect of mitigation measures on landslide hazard using 2D numerical runout modelling

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Abstract Landslide mitigation measures are used to reduce the risk affecting mountain communities. The quantitative estimation of the change or reduction in risk, after implementing mitigation measures, requires modeling of past events and the forward prediction of possible future occurences. However, the forward-prediction of landslide hazard is subjected to uncertainties due to the lack of knowledge on some key aspects like the possible source volume that can be triggered and model parameters that determine the landslide runout. In this study, a back-analysis of a debris flow event was carried out using MassMov2D to create a set of parameter ranges for forward-predicting runouts with mitigation measures. We approached the issue of uncertainty by systematically sampling parameters from wide ranges and running hundreds of different runout scenarios. Simulations from back-analysis were compared with the forward-predicted models to determine changes in the spread and intensity of debris flows affecting elements at risk (e.g. houses and roads). This study is a first step towards a quantitative risk assessment (QRA) being carried out within the EC FP-7 funded CHANGES network (Grant Agreement No. 263953).

Keywords Landslide runout, 2D numerical modelling, landslide mitigation, landslide hazard and risk

Introduction

Numerical 2D runout models are used to study the flow behaviour of landslide runouts and to produce hazard maps for areas at risk (e.g. alluvial and debris fans). More recently, 2D runout models are being applied to forward predict or forecast the effect of existing mitigation measures on future landslide and debris flow runouts, deposit heights and velocities (Takahashi 2009; Graf and McArdell 2011; Liu et al. 2012). However, using model parameters from back-analyses to forward-predict future runouts can lead to uncertainties in the modelling results (Pirulli 2010), especially if parameters from "past" events are used with "new" DEMs containing mitigations measures. Therefore, it is necessary to produce multiple scenarios in forward predictive modelling of debris flows when analysing the effectiveness of mitigation measures.

We propose in this study to use parametric sampling from ranges based on back-analysis of past events and expert knowledge to forward predict multiple debris flow runout scenarios with recently constructed mitigation measures using a high resolution DEM. The goal is to analyse whether infrastructure in the study area is still at risk of being hit by debris flows. This information can be used as a first step in determining the quantitative change in risk and the residual risk after implementing mitigation measures.

Study area and mitigation measures

The Abitato Cucco settlement in the municipality of Malborghetto-Valbruna forms a section of the Val Canale valley of the Fella River basin (Friuli-Venezia Giulia region, Eastern Italian Alps). On the 29th of August 2003, a debris flow was triggered by a severe rainfall event, mobilizing approximately 10.000 m^3 of debris which breached an existing mitigation barrier. Deposit heights exceeding 2m affected 13 to 14 houses (Fig. 1).

Fig. 1 (Left) The Abitato Cucco 2003 debris flow from the initiation to the deposit zone and (right) the breach of the barrier which damaged several houses.

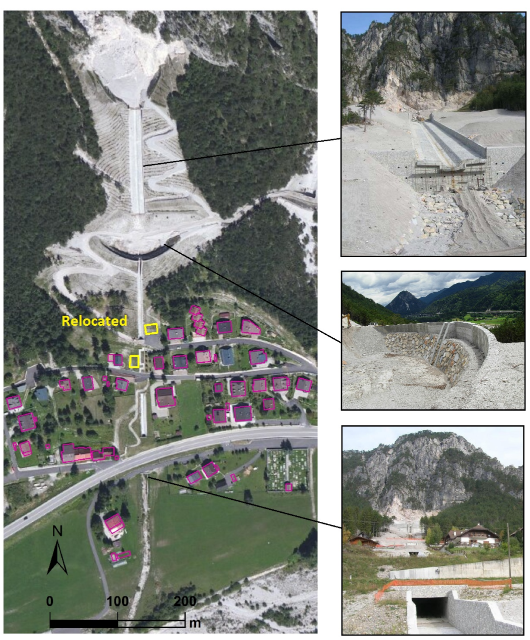

Fig. 2 The mitigation measures constructed at the Abitato Cucco basin following the 2003 event, including the two houses that were relocated.

An estimated total of 1 million cubic meters of debris and sediments in the Val Canale valley were mobilized (Tropeano et al. 2004). Some of the recorded rainfall values that triggered the event were: 88.6, 233.4 and 343.0 mm for periods of 1, 3 and 6 hours, respectively (Calligaris and Zini 2012). According to the analysis of rainfall data, the Abitato Cucco debris flow had an estimated return period of 500 years.

After the 2003 event, the Civil Protection of the Friuli-Venezia Giulia region started works on new mitigation measures. Fig. 2 shows the changes made at the Abitato Cucco area. A small retention basin was constructed at the upper part with a 10m deep retention dam in the middle-section, followed by a channel with a series of culverts leading to the Fella River. Two houses were relocated due to this adjustment.

Numerical runout modelling and back analysis

The Abitato Cucco debris flow was back-analysed by Calligaris and Zini (2012) with the commercial Flo-2D software. They used a 5m DEM acquired from a pre-event laser scanning. Then an attempt was made to forward-predict a debris flow by manually manipulating the 5m DEM to simulate the new mitigation measures based on field observations from 2007. However, after the 2003 event, thousands of cubic meters of material were removed, which completely changed the morphology of the area. Therefore, a new 1m DEM was acquired in June 2008 by the Civil Protection of the Friuli-Venezia Giulia region, which includes the completed mitigation works. Before this DEM can be used for forward-prediction, a back-analysis is required according to the numerical runout model that is chosen.

In this study, we applied the two dimensional single-phase MassMov2D runout model (Beguería et al. 2009) running in the PCRaster GIS environmental modelling software (Wesseling et al. 1996; Karssenberg et al. 2001). There are several reasons for this choice: (1) the model runs in a free and powerful open-source environment, (2) simulation times are faster than other conventional runout modelling software like Flo-2D or RAMMS, (3) different rheologies (e.g. Voellmy, Bingham and Coulomb friction) can be applied and compared with one another, (4) users can add their own rheology or adjust and implement the model code to their own needs, (5) and finally, batch-file capabilities can easily produce hundreds or thousands of models within several hours for model calibration, sensitivity analyses or stochastic approaches. For detailed information on the description and governing equations of MassMov2D, the reader is referred to Beguería et al. (2009).

After testing different rheologies in MassMov2D, the Voellmy rheology performed the best. The initiation volume was represented as a block release polygon with a specific height (m). This volume was released at the start of the deposit zone (Fig. 1). A total of 5 parameters were calibrated in the Abitato Cucco back-analysis: the debris flow release volume (*V*), the debris flow bulk density (*D*), the Chézy roughness coefficient (ξ), the basal friction angle (μ) and the angle of internal friction (α). The parameters were systematically sampled in equal intervals and equal probability from a very wide range to produce 400 simulations using the pre-2003 event 5m DEM. The best performing model parameter ranges are shown in Tab. 1.

Table 1 Model parameter ranges used in the 400 simulations of the 2003 debris flow event and the best performing values obtained from the back-analysis.

Model parameters	Ranges used	Best performing values
Release volume, V (m^3)	4000 - 20000	12000 - 16000
Debris flow bulk density, D (kg/m^3)	1700 - 2200	1850 - 2000
Chézy roughness coefficient, ξ (m/s^2)	10 - 3000	100 - 600
Basal friction angle, μ (°)	5 - 50	5 - 15
Angle of internal friction, α (°)	5 - 50	15 - 40

The required debris flow initiation volume for back analysis ranged at 12.000-14.000 m^3, which is slightly higher than the original estimation of 10.000 m^3 made by Calligaris and Zini (2012). According to Tropeano et al. (2004) the bulk density ranged from 1700 to 2200 kg/m^3, which is in agreement with our best performing values. The Chézy roughness coefficient was purely determined through back-analysis results. Also, due to lack of field samples and laboratory analysis, friction angles (μ, α) were approximated from model calibrations.

Fig. 3 shows the best two performing models in the back-analysis of the 2003 debris flow. The first model does well estimating the deposit height with a slight underestimation of the runout distance (Fig. 3a). The second model gives a more accurate runout extent but with slight overestimations of deposit height at the debris flow toe, and underestimates the height behind the mitigation barrier (Fig. 3b).

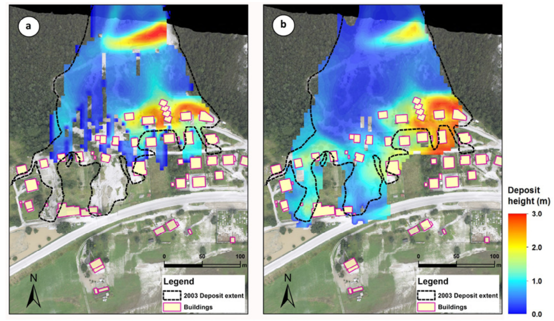

Fig. 3 Back-analysis in 5m resolution of the 2003 event: (a) model with the best estimation of deposit heights (V=13000 m^3, D=1850 kg/m^3, ξ=300 m/s^2, μ=10°, α=20°) and (b) the best performing model in terms of runout extent (V=16000 m^3, D=2000 kg/m^3, ξ=600 m/s^2, μ=12°, α=15°).

Forward-prediction modelling

Forward-prediction modelling with the latest DEM (June, 2008) was carried out first in 5m resolution by up-scaling the 1 m DEM in order to directly compare the 2008 situation with 2003. This was followed by modelling in the original 1 m resolution in order to forward-predict the most accurate runout extent and heights. We also compared the 5m model with the 1m model to analyse the effect of the DEM resolution on the runout modelling.

The best performing range of parameter values in the back-analysis (Tab. 1) were used to carry out 100 simulations for forward-prediction scenarios using the 5 m DEM. The results of the 100 5m resolution models can be classified into three main scenarios: (1) no debris flow breaches, (2) breaching of the retention dam and lower channel, or (3) breaching only at the lower channel (Fig. 4).

All 5m runout models show an accumulation of debris of more than 3 meters at the upstream artificial basin. This indicates that the mitigation system significantly decreases the possibility of large debris flow heights to reach downstream. The maximum deposit height in the most extreme scenarios near the houses is no more than 0.85 m. This is a substantial decrease compared to the 2003 deposit heights of 2.0 to 2.5 m. Breaching of the dam and lower channel occurs mainly towards the east side of the settlement. The western part of the settlement is almost unaffected. Scenario 1 models show deposits of maximum 0.15 m on the eastern channel banks, while scenario 2 and 3 have more significant deposit heights and flow velocities. The most extreme scenarios affect approximately 8 to 10 houses, with scenario 2 type simulations affecting a maximum of 3 to 4 houses.

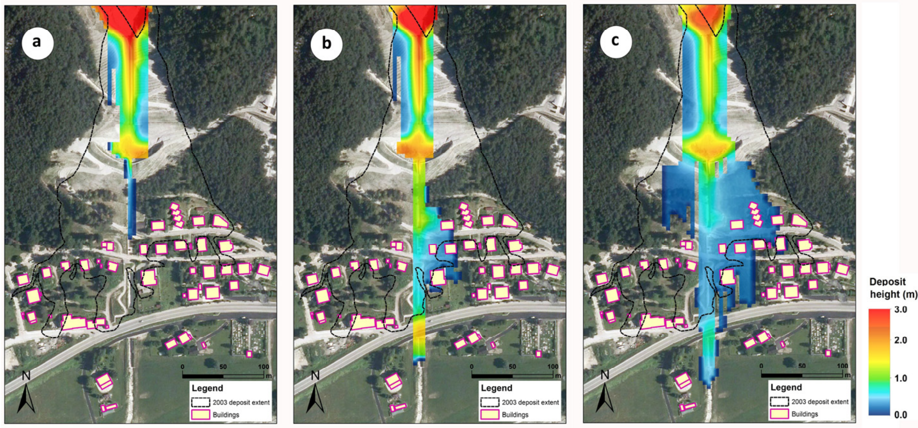

Fig. 4 Examples of the three main type of forward prediction scenarios using the latest upscaled 5m DEM (June, 2008): (a) no breaching at the retention dam (V=12000 m^3, D=2000 kg/m^3, ξ=300 m/s^2, μ=10°, α=10°), (b) debris breaches only at the lower channel (V=12000 m^3, D=2000 kg/m^3, ξ=100 m/s^2, μ=8°, α=15°), and (c) breaching of the flow at the dam and lower channel areas (V=12000 m^3, D=2000 kg/m^3, ξ=100 m/s^2, μ=5°, α=40°).

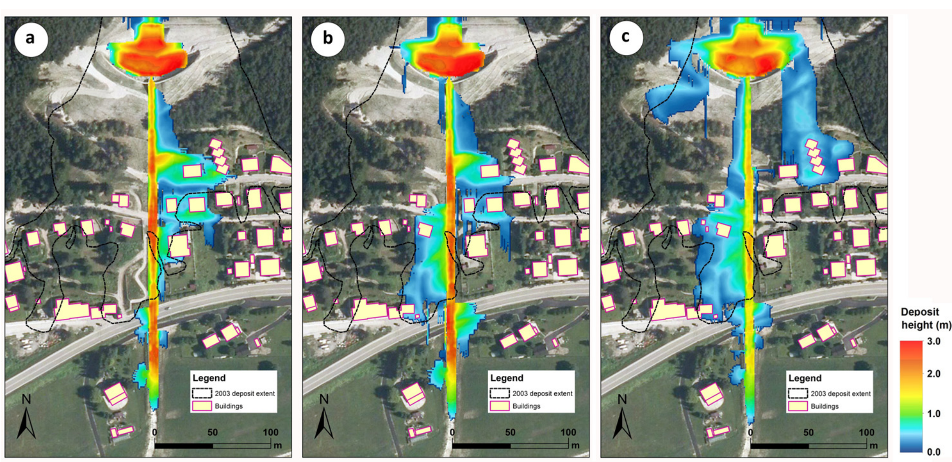

Fig. 5 The three general types of forward-predicted scenarios using the original 1m DEM (June, 2008): (a) debris flow breaching at the east channel bank (V=13000 m^3, D=1850 kg/m^3, ξ=100 m/s^2, μ=10°, α=30°), (b) breaching at both sides of the channel (V=12000 m^3, D=1850 kg/m^3, ξ=100 m/s^2, μ=8°, α=30°), and (c) breaching at the retention dam and lower channel (V=13000 m^3, D=1850 kg/m^3, ξ=100 m/s^2, μ=8°, α=40°).

A total of 50 forward-prediction simulations were produced using the 1 m DEM due to time constraints of modelling in a 1 m resolution. A simulation averaged around 30 to 40 minutes compared to a 3 to 5 minute simulation time in 5 m resolution. Similar to the 5m simulations, the 1m models were also categorized into scenario types. Non-breaching scenarios in 1m resolution were less common than in the 5m simulations. Therefore, we defined the 1m scenarios into the following three types: (1) breaching at the east channel bank (2) breaching at both channel banks and (3) breaching at the dam and lower channel area (Fig. 5).

The 1m simulations give a very different view on possible scenarios due to the more accurate depiction of the dam and channel geometry. The modelled debris flows are more confined, pushing the higher deposits further downstream. The thicker deposits that stopped at the upper basin in the 5m models are now located near the retention dam in the 1m simulations. Breaches at the lower channel are much more subtle and follow better the topography, with higher deposits found near the houses next to the channel. The average outputs of both 5m and 1m simulations can be compared with one another in Tab. 2. The results show that 1m model scenarios generally affect less houses, but show higher intensity values. This is possibly due to the more confined flow in the 1m simulations, forcing the velocity and height to slightly increase in narrower sections of the flow.

Table 2 Average modelled intensities and number of houses affected for all scenario types (3 scenarios in 5m and 1m resolution).

Forward predictions	Maximum flow height near houses	Maximum velocity near houses	Number of houses affected
Scenario 1 (5m)	0.15 m	0 m/s	0
Scenario 2 (5m)	0.52 m	2.2 m/s	4 - 5
Scenario 3 (5m)	0.85 m	3.6 m/s	8 - 10
Scenario 1 (1m)	1.05 m	3.9 m/s	2 - 3
Scenario 2 (1m)	0.76 m	2.7 m/s	3 - 4
Scenario 3 (1m)	0.47 m	1.8 m/s	5 - 6

Discussion and conclusions

The limitations of forward-predicting landslide runouts can be related to several assumptions that have been made in this study. Forward-analysis was carried out using a similar initiation volume as the 2003 event. However, it is known that debris flow source areas need time to recharge and accumulate enough sediment in order for a similar past event to reoccur (Glade 2005). This problem can therefore cause changes in the magnitude of a certain return period. A thorough assessment of the source area is required to analyse possible changes in debris recharge, which accordingly can change the input initiation volume for modelling.

Debris flow entrainment was assumed to be part of the initiation volume. Despite the relative short distance between source and deposit zones, entrainment can still play a substantial role in the formation of the final deposit heights and velocities in deposit zones (McDougall and Hungr 2005; Hussin et al. 2012). Furthermore, the use of a block release polygon instead of a hydrograph can have some disadvantages. Hydrographs are able to more accurately describe boundary conditions, surges and the timing of flows reaching deposit zones (Hürlimann et al. 2003).

The DEM resolution has shown to be very significant in modelling debris flow runouts, especially in artificially channelized areas which are more difficult to model than flows spreading on open slopes or debris fans. The high resolution 1m runout simulations show more realistic flow scenarios, where the retention dam and channels are more accurately defined. Differences in flow extent and heights between the 5m and 1m models change the predicted areas and houses being affected. Thus, it is highly recommended to model debris flows in the highest resolution possible when assessing the effectiveness of mitigation strategies.

The accurate representation of different types of mitigation measures in a DEM can be very difficult, regardless of the detail or resolution of the DEM. In our work, we assumed the culverts to be an open channel system, simulating their inflow points by creating very small obstacles in the channel bed. This assumption was required due to the restriction of our chosen model. Other models like Flo-2D are capable of modelling with culverts, tunnels and other obstacles. Therefore, comparing the two different models is planned in the near future for our continuing research.

This study applied specific ranges from back-analysis to forward-predict possible future runouts. However, some model parameters, like the Chézy roughness coefficient, cannot be measured in laboratory or field studies . These parameters can only be obtained by calibrating runout models using a DEM representing the past event. Therefore, applying back-calibrated parameters for forward-prediction using completely different DEMs causes a source of uncertainty in prediction outputs. We have tried to approach this uncertainty by simulating many runs and classifying the large amount of produced models into several scenario types. Our approach gives some indications of possible types of scenarios and the number of buildings that can be affected in the future. The application of wider parameter ranges to produce many landslide runout simulations, results in multiple possible scenarios. This is an indication of the importance of acknowledging uncertainties in landslide mitigation planning and the need to address the difficulties in predicting residual landslide risk.

Acknowledgments

The work in this paper is part of the CHANGES project, a Marie Curie Initial Training Network funded by the European Commission's 7th Framework Programme (Grant Agreement No. 263953). We acknowledge our gratitude to all our collegues at CNR-IRPI (Padova and Perugia) who continuely support us in this ongoing research. We thank the Civil Protection (Palmanova) and Geological Survey (Trieste) of the Friuli-Venezia Giulia region for their data sharing and cooperation.

Finally, many thanks go to Dr. Chiara Calligaris (Department of Mathematics and Geosciences, University of Trieste) for sharing her important experience on surveying and modelling of landslides in our study area.

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