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Additional torrent control strategies on debris flow alluvial fans with extremely high vulnerable settlements

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Abstract: Recent extreme debris flow and hyper-concentrated flow events in the Alpine Regions have shown on the one hand the enormous destructive impact power on buildings, bridges and roads, and on the other hand, the limits of "classical" torrent control measures. Due to reliability constrained efficiency of consolidation protection measures with unsatisfactory performance in case of extreme events the sediment load volume is higher than expected due to remobilization phenomena. In many cases check dams with sediment retention or sorting function don't function properly and the openings are immediately obstructed. The results of an extended backward and forward oriented investigation clearly suggest a change of paradigm for the torrent control strategy at least where the possibility for hazard reduction is extremely limited, if pursuit with the construction of classical torrent control measures. This work suggests enlarging the toolkit for torrent control by going beyond "object protection" for buildings on the debris flow phenomena affected alluvial fans. The number of endangered objects located in the red, blue and yellow hazard zone has to be reduced to a minimum. Here we propose, starting from an in-depth understanding of the involved processes and overland flow dynamics, the construction of protection structures, the specific reinforcement and where necessary a functional reshaping of building's boundaries, terrain breaklines, and roads in order to obtain a maximum damage reduction diverting the flow towards sectors where the value at risk is lower. The goal is to identify the set of construction elements that minimizes the expected damage. It's an iterative procedure that involves a series of numerical simulations corresponding to each particular protection configuration. A simplifying graph theoretic schematization of the overland flow dynamics permits to identify suitable locations for the construction of these protection elements and to reduce the computational efforts reducing the number of simulations otherwise required. The procedure has been applied to a case study.

Keywords: debris flow, natural hazards, object protection, risk analysis, torrent control.

Introduction

An in-depth analysis in form of a backward oriented investigation of the debris flow and hyper concentrated flow events, that have been documented since 1998 and which data have been made available in a proper database, shows on the one hand a series of significant results concerning the relationship between reliability of “classical”, in stream located, torrent control protection measures and event’s magnitude and their functional efficiency and the damage exposure of the objects at risk on alluvial fans on the other hand. Significant performance deviations have been registered for each of the following characteristics of an ideal protection system (Mazzorana, 2007):
- long durability (high reliability), easy and cheap maintainability
- high functionality (efficiency) with substantial mitigation effects for high return period events and a proper mitigation effect for low return period events
- high sediment transport regulation capacity with progressive reduction of the remaining sediment yield potential
- Low uncertainties about protection system responses to extreme events, easy integration and more effective implementation of early warning systems
- Resilient response to extreme loadings (beyond design return period intensities)

Once the peak discharge overloads the capacity of the alluvial fan channel cross sections, overland flow is triggered by the debris flow surplus volume. The objects at risk in most of the cases are directly exposed to the debris flow impact forces. In recent years first steps toward the ideation and implementation of integral constructive risk reduction approaches have been made. Here we report just some examples. Egli (1996, 2005) gives a complete overview of effective object protection techniques for mass movements, water related hazards and avalanches. Willi et al. (2006) explains how differentiated flood protection has been implemented at the Engelberger Aa. In this case the risk reduction for the settlements is realized from a technical perspective by a controlled dike failure that diverts lateral overflow towards floodplain areas where the value at risk is lower and where the flood effects can be controlled. Dike reinforcements and channel geometry adaptations complete the set of technical measures that are integrated with early warning and rescue action plans. Scherer et al. (2005) proposes a flood impact reduction concept for the city of Vipiteno in South Tyrol, where the city, in case of inundation, is protected by so called primary and secondary defence lines made up of iterative and temporary flood protection elements. Here we propose a stepwise problem solving approach that, starting from system response analysis (backward and forward oriented investigation) and a graph theory based representation of the dynamic behaviour of debris flow processes on alluvial fans, provides the framework for the identification of the set of construction elements that minimizes the expected damage. First an overview of the problem solving approach is given, then the graph theoretic elements that allow the simplified representation of flow phenomena on alluvial fans are presented and applied to practical cases and finally it is shown for one case study how to find the set of construction elements that maximizes the risk reduction.

Overview of the problem solving approach

The following list gives an overview of the problem solving approach:

1) The first step of the procedure is the system response analysis through backward and forward oriented investigation of the debris flow behaviour on the alluvial fan. The goal is to provide a wide range of scenarios in order to “capture” at least to a certain extent the variability of deposition phenomena as a results of debris flows of different magnitude, different rheological behaviours, unforeseen cross-sectional obstructions (e.g. due to woody debris transport) or other momentary “configurations” that cause unexpected diversions of the flow. The backward oriented investigation can provide, depending on the quality of the available data, a first idea of possible flow patterns and preferential flow directions. If deposition heights have been recorded, the deposition volume can be estimated. It has to be checked, on the basis of a geomorphological investigation of the alluvial fan, if other flow patterns could have existed in the past and could potentially be reactivated in case of extreme events. The forward oriented investigation consists in performing a series of simulations with a 2D debris flow propagation model as follows:
   a) Debris flow simulation on the alluvial fan for events of relevant return period (e.g. recommendations for the production of hazard zoning maps) under the hypothesis that the “channel geometry” on the alluvial fan is not reduced and therefore available for propagation.
   b) Under the same loading conditions of the system, assume that, due to in stream depositional phenomena, the “channel geometry” is not available for flow propagation.
   c) Under the same loading conditions assume that the “channel geometry” is available for flow propagation except at bridges, culverts and abrupt channel restrictions.
   d) Take into consideration possible climate change scenarios. According to the research results in this field increase the loading conditions of the system (duration and maximum discharge peak of the debris flow).

As a synthesis of the backward and forward investigation, the maximum flow depths and the maximum velocity maps are produced. These maps are called maximum
intensity propagation maps. Also the simulation results for each output time step interval are taken into consideration.

2) The next step consists in an overlay of the maximum intensity propagation map and the vulnerability map in order to obtain the “specific risk” map.

3) On the basis of the maps produced at points 1 and 2, the simplified graph theoretic representation of the debris flow dynamics follows.

4) Through heuristic engineering judgement the protection strategy is defined by determining the location and the type of additional risk mitigating object protection measures that “control” the flow and/or modify the flow propagation patterns.

5) According to the “selected” protection strategy the digital terrain model is modified and a new series of simulations is performed in full analogy with the forward oriented investigation described at point 1. A new risk evaluation follows. While the new maximum propagation map gives investigation to further the protection strategies, the comparison between the original risk situation and the new one shows the obtained risk reduction.

6) Steps 3 to 5 have to be repeated until the maximum risk reduction is obtained. The whole procedure is shown in the following flow chart (see figure 1).

![Flow chart of the problem solving approach](image)

**Figure 1.** Flow chart of the problem solving approach

**Representation of debris flow dynamics on alluvial fans: a graph theoretic approach**

In this work graph theory is used to represent debris flow dynamics on alluvial fans (Ottmann et al., 2002). A digraph $G = \{V, E\}$ consists of a set $V = \{1, 2, \ldots, |V|\}$ of vertices and a set $E \subseteq V \times V$ of edges or arcs. A pair $(v, v') \in E$ is called arc from $v$ (start vertex) to $v'$ (end vertex); $v$ and $v'$ are adjacent and $v$ (and also $v'$) is incident with $e$. The vertices are represented by points and the edges by arrows with the arrow head toward the end vertex. We choose to store the graph objects in an adjacency list. The structure is shown in the next figure (left). For the scope of this work we identify a general graph structure (figure 2 on the right side) that combined correctly can reproduce, to an allowable degree of simplification, the “macroscopic” flow characteristics on the alluvial fan. This fundamental sub graph and its modifications consist of 1, 2, \ldots, n input vertices and arcs, 2 intermediary vertices and arcs and 0, 1, 2, \ldots, m output arcs and vertices. The second intermediary vertex, from which the output arcs depart, is the abstraction of any feature on the alluvial fan that influences significantly the flow. The arcs are labelled in relation to the specific risk. This fundamental sub graph can be used also to model in a simplified fashion the function of sediment dosing check dams.
Similarly a channel tract with a partially obstructed bridge cross section, overflowing phenomena at the right and left side of the channel and backwater effects upstream of the bridge can be modelled (see figure 3).

Figure 3. Graph representation of a sediment dosing check dam (left) and of a channel with obstruction and lateral overflow (right)

Given the maximum intensity propagation map –MIPM- and the specific risk map –SRM-, the relevant flow trajectories can be identified and the specific risk vertices –SRV-, as well as the flow changing vertices –FCV-, can be defined. Interpreting the flow patterns, taking into consideration both MIPM and SRM, the propagation graph –PG- is constructed and defined as follows: \( PG = \{ SRV \cup FCV, FA \} \), where FA is the set of flow arcs. The next steps consist in constructing the adjacency list of the digraph and in assigning the risk costs –RC- to the flow arcs –FA. The assigned risk costs derive from a risk analysis that takes into account the intensities of the process, the vulnerability of the damage exposed objects. The vertices are coloured according to the risk exposure, the arcs are labelled with the corresponding specific risk costs. The sources (roots) and the exit vertices are identified. A set of relevant risk objects to be protected are selected from SRV. The following paths are calculated: 1) maximum risk cost paths to exit vertices – MaxRCPtoEV- starting from root vertices, 2) minimum risk cost paths to exit vertices – MinRCPtoEV- starting from root vertices, 3) risk cost paths to the selected SRVs. The calculated paths at points 1, 2 and 3 are evidenced in the digraph.

A set of heuristics (principles) –P- can be used alone, or in combination, to modify the digraph in order to obtain a satisfactory risk reduction (Zobel, 2006). For some principle also the complementary principle –CP- can be applied in specific situations. Here a list of 7 principles is proposed:
1) P: Decomposition (diversion, deviation) ↔ CP: Composition (union)
   E.g. P: deviation (collection) of MaxRCPtoEV towards MinRCPtoEV or towards low impact sectors
2) P: Separation (detachment) ↔ CP: Addition
E.g. P: Let $ROV \subseteq SRV$ be a set of relevant objects to be protected, then through a separation measure, part of the arcs – FA- that end in the vertices – ROV- are eliminated.

3) P: Combination  
E.g. P: The implemented protection strategy is “inspired” by different protection principles. The problem is tackled from different perspectives

4) P: Multipurpose use $\leftrightarrow$ CP: optimal single function performance  
E.g. P: Protection measure obtained by landscape reshaping do not drastically interfere with agricultural practices when the system is not interested by natural hazard phenomena

5) P: Shortest path (minimum risk path)  
E.g. P: MinRCPtoEV should be systematically favoured and the discharge should be conveyed toward it (adaptations of cross sectional geometry)

6) P: Smoothing in space and time (dosing, retention) $\leftrightarrow$ CP: Controlled overloading  
E.g. P: This is one of the most important impact reduction principles that should be considered throughout the whole protection strategy, e.g. favouring “natural” deposition phenomena in low risk sectors (Armanini, 2001)

E.g. CP: Controlled dike failure at a predefined location to unload the rest of the system

7) P: Substitution (Integration) of expensive permanent protection components with temporary protection components

Case study: Weissenbacher torrent

The Weissenbacher torrent basin (0.65 km²) is located in the Aurino basin in the eastern part of the Autonomous Province of Bolzano. Concerning the backward oriented investigation a relevant debris flow event happened in the Weissenbacher torrent at 13th August 2002. Concentrated rainfall was about 40 mm in 50 min coming from S-E direction. The debris flow event was triggered in the starting zone 5 smaller landslides (approx. 3500 m³). In the transit zone the debris flow caused deep and lateral erosion phenomena (approx. 7200 m³). The total debris flow volume that was approaching the alluvial fan apex was approx. 9500 m³, while approx. 1200 m³ were deposited along the incised channel. At the alluvial fan apex a consistent of the debris flow volume (coarser material) was deposited, while the remaining part propagated in five overland flow limbs and along the channel on the alluvial fan. Concerning in stream structures one culvert was completely destroyed, while another one was clogged. Several roads and approx. 4 ha agricultural land have been covered by the debris flow material and had to be cleared. Only four houses were damaged, but not severely. The next figure gives an overview of the event. Concerning the forward oriented investigation, first a hydrological analysis has been performed with the HEC-HMS model in order to obtain the hydrograph. The peak discharge of the debris flow was estimated using Takahashi’s formula (Takahashi, 1991). Different scenarios have been simulated with the propagation model FLO-2D. Figure 4 shows the simulation results.

![Figure 4. Left: simulation (depth - velocity) right: Event 13th August 2002](image-url)
Figure 5. Maximum risk cost paths for source 1 and 2 respectively;

Figure 6. Minimum risk cost paths for source 1 and 2 respectively
Risk categories have been assigned to each vertex and the arcs have been labelled with the risk costs. The minimum and maximum risk cost paths for each root (source) of the graph have been determined. The results are shown in the figures 5 and 6.

The results of the methodology applied to the test case suggest the locations where it’s efficient to intervene with technical measures and the heuristics indicate possible solution principles for risk mitigation problems. The definite choice and design of the technical measures that implement the solution strategies relies on expert knowledge. Consequently the heuristics have been applied and the protection strategy shown in the next figure has been developed. It’s a combination of deviation and object protection measures in addition to measures that favour debris flow deposition phenomena in “low risk” alluvial fan sectors. The deviation protection measures consist in dam construction in combination of local reshaping and remodelling of the channel geometry. The protection strategy (see figure 7) includes also the removal of “weak points” along the torrents.

**Figure 7.** The proposed protection strategy

A series of additional simulations have been performed in order to check the risk reduction effect of the proposed protection strategy. The results are shown in the figure 8.

**Figure 8.** Simulation with protection strategy

**Conclusions**

In this work we proposed a procedure that structures the relevant information and knowledge from backward and forward investigation by means of the system response analysis resulting in a graph theoretic representation of flow patterns and object – flow interactions. On this basis a risk analysis can be methodically performed. In addition we proposed a set of heuristics that support the design of protection measures that efficiently reduce the overall risk exposure. The application of the case study -Weissenbach torrent- has shown that the procedure can successfully be applied to the investigation of “multi-source” debris flow related hazards in vulnerable regions. The calculation of maximum and minimum risk cost path as well as the risk cost path for the relevant objects is a crucial step
for the definition of the protection strategies that become comparable. The decision making process takes advantage from the availability of these indicators. Further research activities in this field will focus on the applicability of this procedure to flood related risk assessment. An automatic graph generation algorithm, that has to be added to complete the procedure, could facilitate the analysis of larger scale phenomena.

Hazard mitigation and increased risk reduction through strategically located control elements is an interdisciplinary task. The protection elements have to be hydraulically effective and suitable from a landscape-architectural view. Last but not least, the affected population has to be involved from the first planning steps with a consensus building approach. A transparent communication of hazard, risk and the inherent limits of “classical” protection measures is absolutely necessary in order to prepare the ground for a general acceptance of these additional protection strategies.

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