2 Local-Scale Risk Analysis and Mitigation of Debris Flow Endangering a Densely Populated Urban Area: A Case Study from Tyrol, AT

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Abstract

Debris flows present a serious threat to Alpine settlements and infrastructure. A case in point is the city Innsbruck (Tyrol, Austria). In case of extremely heavy precipitation in the Höttingerbach catchment, located in the city's north-west, flooding and debris flow may endanger Innsbruck's district Hötting. The calculation of the debris flow risk and the discussion of the type and impact of a potential risk mitigation measure, are presented in the following. The risk analysis consisted of the following steps: (a) determining debris flow hazard potential; (b) estimating damage potential of material assets and persons; (c) combining (a) and (b) to calculate the societal risk. The results of the risk analysis revealed Hötting's high susceptibility towards debris flow and flooding, with 542 houses and over 4,100 persons potentially exposed. Therefore, a risk mitigation measure was elaborated, consisting of a water retention basin near the apex of the alluvial fan. An analysis of the potential impact of this measure on the risk situation showed a distinct reduction of the potential damage to material assets and persons as well as a positive cost-benefit ratio.

Keywords

Risk management • Debris flow • Retention basin • Hydraulic engineering • Höttingerbach Tyrol

2.1 Risk Analysis

Recent major flood, avalanche and debris flow events have brought about the understanding that a complete protection against natural hazards is neither economically nor environmentally feasible (Keiler and Fuchs 2007). Scarcity of public budgets entail the need for highly cost-efficient mitigation measures (Fuchs et al. 2008). Thus, the risk concept was adapted to natural hazard management throughout the last 15 years, in an attempt to foster an integral, holistic and sustainable risk-based approach (Brundl et al. 2009; Crozier 2005; Hollenstein et al. 2004). In natural hazard research, quantitative risk is generally defined as a function of (i) the probability of the occurrence of a hazardous process (hazard potential) and (ii) its possible consequences in terms of damage to material assets and persons (e.g. (Fuchs et al. 2007)).

In the scope of the presented study, the **hazard potential** was derived using terrain analysis, base maps, remote sensing imagery and past event cadastres, as well as expert knowledge and physical modelling. The pre-mitigation hazard potential was defined for the following return periods:

- 150-year event (customary Austrian design event)
- 30 and 300-year event (to allow for a more comprehensive analysis and gearing to EU- and Swiss standards

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In order to assess the effectiveness of the planned mitigation measure at the fan apex, post-mitigation scenarios (30-, 150- and 300-year event) were included in the risk analysis, adding to the three above-mentioned pre-mitigation scenarios. All six scenarios were delineated according to the debris flow hazard mapping criteria defined in the corresponding Austrian guidelines (BMLFUW 2011). The results consisted of digital maps of the study site, highlighting the classified debris flow intensity for each scenario.

The **damage potential** of material assets and persons was determined on a local level, utilising a GIS-based approach, which draws on the current literature (e.g. Keiler et al. (2006), Brundl et al. (2010)) and the Austrian cost-benefit regulations (BMLFUW 2006). It only considers direct damages, i.e. the immediate physical consequences of the debris flow impact on buildings and persons, not the indirect effects (e.g. socio-economic damages due to road closure). The assessment was based on a wide range of spatial and statistical data (e.g. digital elevation models, orthophotos, building values, number of registered persons per household, etc.), as well as a detailed field survey of the study area. To allow for a thematic differentiation within the risk analysis, the objects of protection were split into different categories (i.e. residential and public buildings; road and supply infrastructure lines; commerce, service and tourism buildings). Furthermore, indicators were defined to describe the damage potential in detail (e.g. material damage in €; number of fatalities). In general, the study area is characterised by a substantial number of large, multi-storey buildings and a generally high density of buildings and persons (1,440/km^2 and 10,090/km^2 respectively).

The results of the damage potential assessment show that 542 buildings with a total value of approximately €412 Million and over 4,100 persons are located in the study area and are thus potentially exposed.

The **societal risk** is defined as the statistically expected average amount of damage [€] and fatalities per year, corresponding to the above-mentioned indicators. It was calculated according to Brundl et al. (2009, 2010) by (i) determining the total expected loss per scenario by spatially intersecting the hazard and damage potential results and calculating the individual expected loss for every object at risk (consequence analysis); (ii) multiplying the expected loss with the frequency of the respective scenario to calculate the societal risk. As no detailed data on the expected flow heights and pressures of the debris flow were available, values for spatial occurrence probability, damage susceptibility and lethality were retrieved from (BMLFUW 2006) and supported by values from (EconoMe 2012).

The results show that taking all scenarios and their respective occurrence probabilities into account, a total risk of €522,000 to material assets is statistically caused by debris flow in Hötting per annum, the major bulk (67 %) of which falls into the category 'residential and public buildings'.

2.2 Risk Mitigation

Based on the results of the risk analysis, an assessment of the technical possibilities and potential benefit of the construction of a mitigation measure above the endangered area was performed. At the fan apex, the river enters an underdimensioned trench, through which it runs along the alluvial fan and under the settlement before entering its tributary, the Inn. As the transport capacity of the trench is limited, large-scale floods can be expected, if its maximum runoff capacity is exceeded. Therefore, a water retention basin, located in the upper part of the alluvial cone was designed, which is intended to limit the water and debris flow material influx to the trench.

The fundamental **hydrological** basis for the conception of the mitigation measure, was the calculation of the expected peak water discharge for the 150-year event from the 6.72 km^2 large Höttingerbach catchment. Austrian legislation requires all mitigation measures constructed by the Austrian Service for Torrent and Avalanche Control to be dimensioned to a 150-year event, therefore the 30- and 300-year event where not explicitly considered in this step. The required hydrological calculation was performed with the surface runoff model ZEMOKOST (Markart et al. 2004; Kammerlander and Kohl 2010). The results of the modelling showed that the peak discharge of the Höttingerbach reaches 20.6 m^3/s, when considering a critical rain duration of 19–26 min in case of a 150-year event. In the worst case, the maximum water volume may reach up to 185,000 m^3 in total. In order to guarantee the high durability of the water retention basin, a peak water discharge of about 45 m^3/s was simulated in the catchment (corresponding to an event with a 5,000 year return period).

From a **hydraulic** point of view, it was necessary to first define the maximum transport capacity of the trench. Due to the density of the surrounding settlement, enlarging the trench was not an option. The trench capacity is limited to 6.94 m^3/s by the flat longitudinal trench ground, which has an inclination of 1 %. This capacity stands in contrast to the above-mentioned expected peak water discharge of 20.6 m^3/s. The base runoff from the Höttingerbach catchment totals 3.09 m^3/s, leaving a residual maximum runoff of 3.86 m^3/s (Gems and Achleitner 2011). The electro-hydraulic control of the water retention basin was defined based on these hydrological and hydraulic calculations. Figure 2.1 gives an overview of the calculated maximum reservoir capacity (red), inflow hydrograph of the 150-year event (black) and

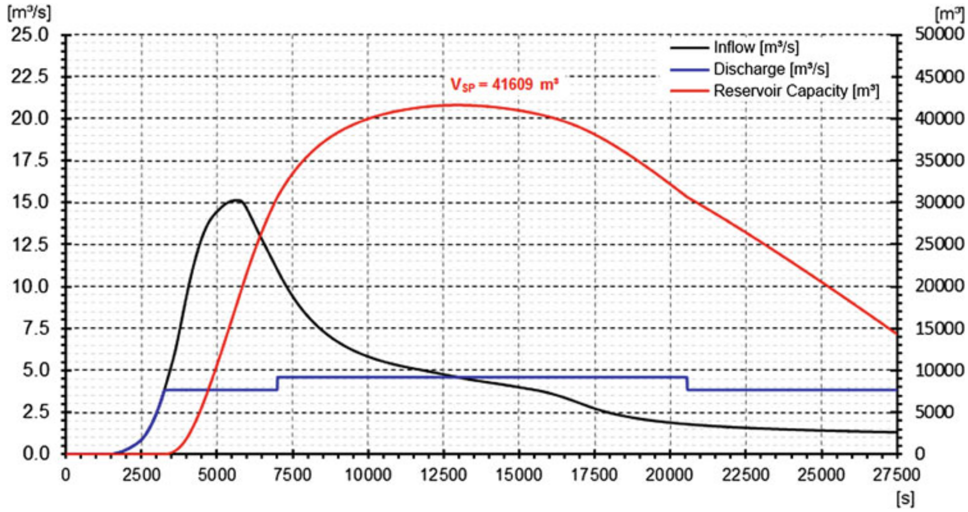

Fig. 2.1 Maximum reservoir capacity (*red*), inflow hydrograph of the 150-year event (*black*) and the throttled water delivery into the trench (*blue*)

the throttled water delivery into the trench (blue). In the course of the project, a retention basin and a flexible net barrier, dimensioned to a 150-year event, were installed above the reservoir, thus retaining the majority of the debris flow material.

A vertical height of the basin's earth dam of 28 m and a maximum water capacity of 41,700 m^3 at a water retention level of 745 m a.s.l. are necessary to accommodate for the scale of the design event (150-year return period). From a **geo-technical** point of view, it was essential to guarantee the impermeability of the whole construction by different loading conditions. The water retention basin is characterised by a core seal, carried out by a bored pile wall, with a depth of 12 m under the river basin. The core of the earth dam is planned to be constructed with different overlapping boreholes filled with armoured concrete. The hydraulic compensation outlet is dimensioned to buffer the design event so the discharge does not exceed the maximum transport capacity of the trench. The construction is grounded on the sedimentary rock of the Höttinger Breccie. Partly fragments of quaternary deposits are located in the area, which however lie above the retention water level. The permeability of the geological base was defined by (Sausgruber et al. 2012). The permeability reaches 5×10^{-5}–8×10^{-5} in a depth of 7–10 m, 1×10^{-5}–2×10^{-5} in a depth of 10–14 m and $<8 \times 10^{-6}$ in a depth of 14–30 m. The permeability of the Höttinger Breccie was defined by a flowmeter. The geological analysis showed, that there are no potential deep-seated gravitational mass movements in the area, which could affect the mitigation measure, if the basin was filled with water. Due to the setup of the mitigation structures described above, only a minimal amount of debris

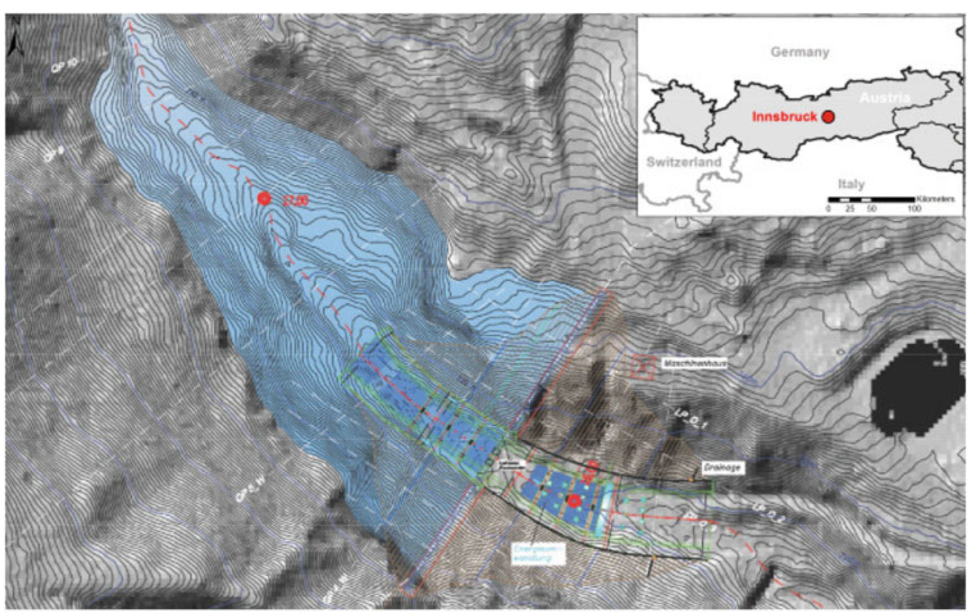

Fig. 2.2 Overview of the location of the test site in Austria and details on the layout of the water retention basin; the *blue* area marks the maximum filling level

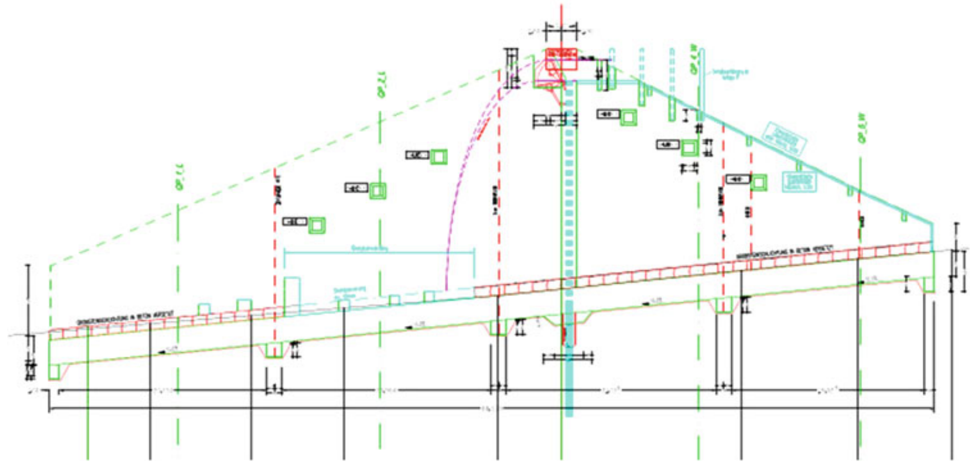

Fig. 2.3 Detailed cross section of the earth dam and the depth of the core seal carried out with the overlapping boreholes filled with armoured concrete

flow material is expected to reach the reservoir. It is therefore dimensioned based on its capacity for clear water. The location of the test site and an overview of the proposed mitigation measure are provided in Fig. 2.2. Figure 2.3 shows a detailed technical drawing of the planned mitigation measure.

2.3 Impact of the Mitigation Measure on Risk in Hötting

The proposed mitigation measure has a significant impact on the risk reduction of debris flow events potentially affecting Innsbruck's district Hötting. As the construction is able to fully mitigate a discharge from the catchment with a 30- and a 150-year return period, as well as significantly reducing the debris flow- affected area of a 300-year event, the societal risk is markedly lowered: In total, the yearly expected damages to material assets can be reduced from €522 M to €18,000, while the number of exposed buildings decreases from 542 to 127 and the number of potentially exposed persons is lowered from 4 100 to 970.

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