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Sensitivity of avalanche risk to vulnerability relations

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ABSTRACT

Long-term avalanche risk assessment is of major importance in mountainous areas. Individual risk methods used for zoning and defense structure design are now gaining popularity in the effort to overcome the major drawbacks of approaches based on high return period events only. They require, for instance, precise vulnerability relations, whereas available knowledge mostly consists in coarse curves inferred from a few catastrophic events. In this paper, we first considerably expand the vulnerability curve sets in use today for reinforced concrete buildings and humans inside them. To do so, we take advantage of the results of a comprehensive reliability analysis of various building types subjected to avalanche loads, and we included humans inside buildings in our results by using different link functions. The fragility curves obtained propose refined destruction (building)/death (people) rates as a function of avalanche pressure that can be used in the risk context exactly like deterministic vulnerability curves.

Second, since land use planning should be done for a reasonably large class of buildings rather than for a very precise single building type, this study shows how a comprehensive risk sensitivity to vulnerability/fragility relation analysis can be conducted. Specifically, we propose bounds and indexes for individual risk estimates and optimally designed defense structures of both theoretical (quantifying uncertainty/variability that cannot be simply expressed in a probabilistic way) and practical (minimal/maximal plausible values) aspects. This is implemented on a typical case study from the French Alps. The results show that individual risk estimates are extremely sensitive to the choice of the vulnerability/fragility relation, whereas optimal design procedures may well be more robust, in accordance with mathematical decision theory. These two outcomes are of crucial importance in practice. For example, the individual risk for buildings and people at various positions in the runout zone spreads over several orders of magnitude. For risk zoning, this suggests that the usual (tri)centennial choice may be seen as optimistic since only abscissas above the 1000-year return period are below standard risk acceptance levels with certainty according to plausible variations of human fragility. On the other hand, the optimal height of a protective dam can be more precisely determined, promoting the use of cost–benefit analyses in avalanche engineering.

1. Introduction

Snow avalanches are a serious threat to mountain communities. For their inhabitants, land use planning and hazard zoning are crucial steps that define where it is “reasonably” safe to build. Standard engineering procedures generally consider high return periods as reference design events, *e.g.* the 30-, 100- and 300-year return period events. For planners, zoning then results from the combination of these with additional social and political considerations. However, this is a simplified means of handling the multivariate danger resulting from impact pressure, flow depth or deposit volume within a single avalanche event, that is to say, all the tangible quantities that describe hazard intensity. Furthermore, high return period-based zoning methods do not explicitly take into account the elements at risk and/or possible budgetary constraints, which does not guarantee that unacceptable exposure levels cannot be reached and/or that the mitigation choices made are optimal.

To overcome these limitations, an integrated quantitative risk evaluation is an appealing additional instrument. This approach is based on a solid formalism (Eckert et al., 2012), for individual or collective risk mapping. Individual risk mapping consists in evaluating the expected damage for a typical element at risk at any position in an avalanche path (Keylock et al., 1999). In contrast, collective risk mapping implies considering a two- to three-dimensional hazard description together with all elements potentially impacted. In both cases, zoning then includes both hazard and elements at risk. Another possible outcome of a quantitative risk approach is the optimal design of mitigation measures based on risk minimisation, that is to say, a cost–benefit assessment performed throughout the hazard distribution and, if possible, over a continuous space of potential decisions to be taken. Mitigation measures of maximal economic efficiency can then be chosen (Eckert et al., 2008a, 2009; Rheinberger et al., 2009). As a consequence of

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these advantages over purely hazard-oriented approaches (high return periods), integral risk management is now gaining popularity among stakeholders, and has increasing importance in practice (Bründl et al., 2009).

Specifically, risk quantification requires combining the model describing avalanche hazard with a quantitative assessment of consequences for one or several elements at risk. The avalanche hazard model consists in the distributions of the characteristics of avalanches that can occur in the site studied. These distributions are (at least partially) site-specific and have to be estimated with historical events as much as possible. Two main approaches exist for workable distributions. “Direct” statistical inference can be used to fit explicit distributions on relevant avalanche data, mainly runout distances (Eckert et al., 2007b; Gauer et al., 2010; Keylock, 2005; Lied and Bakkehoi, 1980; McClung and Lied, 1987). As an alternative, richer but more computationally intensive, statistical–dynamical approaches include hydrodynamical modelling within the probabilistic framework (Ancey et al., 2004; Barbolini and Keylock, 2002; Eckert et al., 2008b), which can be seen as an extension of Salm's method (Salm et al., 1990) to multivariate random inputs. They ensure the joint distribution of all variables of interest, including the spatio-temporal pressure field variable (Eckert et al., 2010). These more detailed intensity distributions can then be combined with the damage susceptibility of elements at risk *i.e.* the vulnerability relation.

Vulnerability curves are increasing curves with values within the range [0,1], expressed as functions of a suitable process intensity, e.g. pressure, flow height, or velocity. When studying avalanche-prone areas, the diversity of elements (people, buildings, infrastructures, *etc.*) exposed implies the use of several curves to represent the overall damage potential. For alpine hazards, existing vulnerability relations mainly focus on buildings. Most of them have been determined based on field data (Cappabianca et al., 2008; Papathoma-Köhle et al., 2010; Schwendtner et al., 2013). These empirical curves have drawbacks in that they are based on scarce underlying data (interpolated with statistical regressions, adding potential approximation errors) and to be somewhat site-dependent (because of different technology choices in different countries, for example). More generally, they sometimes fail to provide trustworthy and unique quantitative damage levels in relation to hazard process.

As a consequence, in the specific case of snow avalanches, numerical approaches have recently emerged to evaluate the vulnerability of buildings more systematically (Bertrand et al., 2010). Indeed, numerical approaches have the major advantage of being implementable whenever needed for as many building types/configurations as necessary, providing a set of vulnerability relations that can be used for risk evaluation. Among existing numerical approaches, the one detailed in Favier et al. (2014) made it possible to obtain fragility curves according to typical limit states of different building types. Limit states are defined according to relevant ultimate mechanical characteristics for the building studied, *e.g.* a maximum allowed displacement or an ultimate strength for a composite material. The limit state definition remains, however, a difficult task, depending on the interaction between the hazardous process and the building (dynamical or quasi-static solicitation) and on the failure scale chosen (local, semi-local, or global).

The distinction between fragility curves and vulnerability curves is important. For a given hazard intensity, fragility curves provide a probability of exceeding a limit state (crudely speaking, a destruction probability), whereas a vulnerability curve provides a deterministic damage index or rate. As stated above, Favier et al. (2014) studied the collapse behaviour of a building within a reliability framework, providing fragility relations quantifying the probability that the entire building would be completely destroyed. On the other hand, in the literature, vulnerability curves are often easier to interpret in terms of a damage fraction of a building that fails. It is noteworthy that a fragility estimate can be seen as a conditional expectancy, averaging over the influence of certain factors possibly included in the “full”, multidimensional, deterministic vulnerability relation (Eckert et al., 2012). As a consequence, from a mathematical point of view, vulnerability and fragility curves can be treated and used similarly in the risk framework. However, their intrinsic difference may induce different interpretations in practice that should be kept in mind while comparing risk estimates obtained with the two approaches.

Decision-makers typically need to link the vulnerability of buildings to the vulnerability of the people inside them. By definition, human vulnerability is always expressed as a fragility, *i.e.* as a probability of an individual death as a function of snow avalanche intensity. To do that, some studies have suggested multiplying building vulnerability/fragility (the distinction is not always clearly made) by a particular coefficient (Wilhelm, 1998). However, usually, human fragility has been for the most part assessed using past events (Arnalds et al., 2004; Barbolini et al., 2004; Jónasson et al., 1999; Keylock and Barbolini, 2001), so that existing curves mainly consist in empirical lethality rates brought together by smoothing approximations. Section 2.1 provides a comprehensive review of existing relations. Their scarcity shows how necessary it is to transpose recent advances in building physical vulnerability/fragility assessment to human fragility assessment.

According to these observations, the first objective of this paper is to provide an updated review of available vulnerability/fragility relations for reinforced concrete (RC) buildings and humans inside them (Section 2). Indeed, RC is a commonly used material in areas endangered by snow avalanches, which ensures reasonable safety in areas with high exposure to avalanche pressure, *i.e.* in areas where up to 30 kPa snow avalanche impact pressures are expected. From this RC vulnerability/fragility curve set, and, specifically, from the fragility curves of Favier et al. (2014), we then deduce a large set of human fragility curves. Linking fragility relations for buildings to human death rates has rarely been done, and we propose four quantitative methods to achieve this goal.

Another major problem in many individual and total risk assessments for land use planning is that the exact technology of existing buildings and/or potential new buildings to be built in the future is unknown or, at least, intrinsically variable. As a consequence, it may not be easy to choose the relevant vulnerability/fragility relation among those in existence today, even though this choice may have a considerable influence on the final risk estimates. The second objective of the paper is therefore to study and quantify risk sensitivity to the choice of the vulnerability/fragility relation, which has never been attempted to date to our knowledge. The study was conducted on individual risk for mapping/zoning purposes and within a decisional procedure aiming at minimising risk with a defense structure construction.

In Section 3, we detail how bounds for risk or optimal solutions to the risk minimisation problem taking into account the variability or (mis)specification of vulnerability/fragility relations can be defined and derived from our systematic building and human fragility curve sets. In Section 4, we apply this methodology to a case study from the French Alps, illustrating how vulnerability/fragility sensitivity logically provides high risk bounds for buildings and humans inside them as well as for optimal protection design. This range of plausible values should be preferred to single values with low robustness for zoning and the design of defense structures. Section 5 discusses the major outcomes of the study, specifically those highly relevant for practice, including comparison with acceptable levels and with the results of standard engineering approaches using 30-, 100-, 300- year, *etc.* return periods as design events. Section 6 summarises and concludes.

2. From building vulnerability to human fragility

2.1. Review of vulnerability and fragility relations for snow avalanches

2.1.1. Physical vulnerability and fragility relations for buildings

Wilhelm (1998) assessed the damage susceptibility of five types of buildings to dense avalanche flows: light construction, mixed