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Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flows

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ABSTRACT

Debris flows are natural processes that cause considerable economic loss and sometimes also casualties. The motion of the debris flow is influenced by both solid and fluid forces making it particularly destructive. Although a large amount of studies regarding the process itself is available in the literature, scientists repeatedly focused on the physical vulnerability of the elements at risk since this is often the key for the reduction of devastating consequences. In the present paper, different approaches for the assessment of physical vulnerability to debris flows are presented, discussed and highlighted through studies from the literature. Their advantages and particular challenges are outlined and studies following a similar approach (e.g. vulnerability curves, vulnerability indicators) are presented and compared. Finally, recommendations for the future are outlined including: (1) better damage documentation for improved datasets, (2) improvement, combination and expansion of existing methods (3) consideration of change for future risk scenarios (4) further research on the interaction between elements at risk and the hazard process including laboratory experiments and (5) consideration of the resilience of buildings in the physical vulnerability assessment.

1. Introduction

Debris flow is one of the most frequent and costly hazard worldwide (Santi et al., 2011). Dilley et al. (2005) suggested that debris flows and landslides claim globally approximately 1000 lives per year. A recent detailed study by Dowling and Santi (2014) showed that this number may be even higher (approximately 1200 fatalities per year) since between 1950 and 2011, at least 77,779 fatalities were recorded worldwide during 213 debris flow events in 38 countries. Most of the victims were documented in South America and Central Asia due to their tectonic activity and high precipitation in combination with densely populated mountain areas. Nevertheless, in Europe and especially in the European Alps, debris flows are also frequent phenomena. Rheinberger et al. (2013) making a rough estimate based on a number of studies concluded that in the European Alps in the last 25 years debris flows have been responsible for the death of 200 people and losses of €5 billion. Only in Austria, between 1972 and 2004, at least 4894 torrential events have been recorded of which 28,7% were characterized as debris flows. The average costs per event are estimated to be approximately 170,000€ concentrated mainly on buildings that suffered approximately two thirds of the losses (Fuchs, 2009). Scientists have made significant advances as far as the understanding of the process is concerned, focusing mainly on modelling and monitoring. At the same time, the interaction between the natural process and the elements at risk has also been the topic of research. The reconstruction of hazard scenarios has been often supported by historical data (Petrucci and Polemio, 2003; Tropeano and Turconi, 2004; Marchi and Cavalli, 2007; Vennari et al., 2016) as well as by the detailed site-specific information such as the one provided by the checklist of Aulitzky (1980). Limited studies have also used historical data to reconstruct vulnerability and to understand the interaction between the process and affected structures (Pilotti et al., 2016). Nevertheless, the variety of approaches available for the assessment of physical vulnerability to debris flows demonstrates that there is no universal method for quantification available. In the present paper a critical review of the existing approaches attempts to outline the benefits and limitations of each method and to draft a series of recommendations for future research.

1.1. Debris flows and their impact

Debris flow is a natural process which may be described as an intermediate process between hyper-concentrated flow, often used instead of the term “debris flood” (Costa, 1984; Costa, 1988; Slaymaker, 1988) and landslide (Calligaris and Zini, 2012). Costa (1988) claims

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that a sediment concentration of 47% by volume and 70% by weight can be considered as the threshold between the hyper-concentrated flows and debris flows. One of the most common definitions is the one of Iverson (1997) who defines debris flows as "masses of poorly sorted sediment, agitated and saturated with water, that surge down slopes in response to gravitational action". Debris flow is very often identified as a landslide type (Cruden and Varnes, 1993; Corominas, 1996; Hungr et al., 2001), however, its impact on the built environment is fundamentally different than the one caused by other landslide types such as shallow landslides, due to the flow movement and the presence of water.

The destructive power of the debris flows is attributed partly to their velocity which may be as high as 15 m/s (Hungr et al., 2001). The onset of the process is particularly rapid since the time they need to cover the distance between the source and the deposition is especially short (Santi et al., 2011). Fortunately, as their initiation is directly related to precipitation, they are more predictable than other landslide types (NOAA-USGS, 2005). Three types of forces are responsible for the destructive power of debris flows: the hydrodynamic force (a combination of the frontal impact of the flow and the drag effect on the sides of the building), the hydrostatic load and the collisional force due to the debris carried by the flow (Zanchetta et al., 2004). Although debris flow is always classified as a flow type landslide, the impact on the buildings shares characteristics of the impact of landslides but also it resembles the impact of floods depending on the content of solid material and the size of transported particles (Mazzorana et al., 2014). Jakob (2005) presented a list of ten consequence levels according to this characteristics ranging from localized damage to small buildings to vast and complete destruction of hundreds of km^2 of arable land. A debris flow may cause destruction of the exterior walls of the building or it may completely destroy those walls by large boulders carried by the flow. Additionally, it may enter the building through building openings and damage equipment which is essential for the functioning of the building, such as the electricity network, the central heating appliance or even the sewage or water system (Fuchs et al., 2007). Debris may enter the main part of the building by breaking windows and doors causing significant destruction of interior features (interior walls, floors) and building content (furniture, equipment) and threatening lives. Additionally, a debris flow, depending on the content of solid material and its size, its volume and velocity may also threaten the stability of the building by eroding its foundations and causing floor overloading and significant structural damage (Fig. 1). Vamvatsikos et al. (2010) suggested that masonry buildings, as well as the external walls of reinforced buildings, may collapse in presence of relatively low flow velocities, whereas, the collapse velocity increases with the number of floors of the building. Moreover, structural features of reinforced concrete buildings (e.g. columns) may collapse at velocities within the range of 15–20 m/s.

A considerable amount of studies is available on the physical vulnerability of buildings to debris flows (Fuchs et al., 2007; Fuchs, 2008; Akbas et al., 2009; Quan Luna et al., 2011; Totschnig et al., 2011), whereas a limited amount deals with the impact on infrastructure such as roads and railway lines (Marchi et al., 2010; Meyer et al., 2015). Additionally, the physical vulnerability of protection structures has been also investigated. Dell' Agnese et al. (2013) used empirical evidence to develop a damage index for the assessment of the vulnerability of check dams to bed load and debris flow events. In the present paper only studies analysing the vulnerability of buildings are considered.

Last but not least, the impact of debris flow on humans is also considerable. Dowling and Santi (2014) created a database including 213 debris flow events from 1950 to 2011 in 38 countries worldwide that resulted in 77,779 deaths. However, two major events in Venezuela (19,000 fatalities) and in Colombia (23,000 fatalities) are responsible for more than half of the fatalities. In general, the highest median fatality rates globally are recorded in Asian and South American countries, whereas the lowest are recorded in the North American countries. Similarly, in European countries debris flows claim a significantly lower number of lives. For example, in Austria, only an average of 2–3 fatalities are recorded annually (Fuchs et al., 2012). The number of fatalities in general depends on the volume of debris flow and the number of people living in the area, however, the relationship of the death toll of events and a number of socioeconomic indicators, such as corruption and GDP per capita was also evident (Dowling and Santi, 2014). Although the present study focuses on the built environment, the number of victims per event in the reviewed studies has been also included in Table 2.

1.2. Physical vulnerability, data requirements and related research

The multi-dimensional nature of vulnerability is responsible for the diversity of definitions available in the literature. Regarding physical vulnerability, one of the most common definitions "vulnerability is the degree of loss to a given element, or set of elements, within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss)" (UNDRO, 1984) suggests that vulnerability equals the degree of loss of an element at risk after the occurrence of a natural process (*ex-post*) and shows the need for empirical data. However, according to UNISDR (2009) vulnerability is defined in a more general and qualitative way as "the characteristics and circumstances of a community, system or asset that makes it susceptible to the damaging effects of a hazard". It is considered to be a pre-existing condition (*ex-ante*) that directly relates to the characteristics of the elements at risk, giving less emphasis on the process itself.

In order to assess the physical vulnerability of buildings to debris flows, but also to other natural hazards, it is essential to acquire knowledge on the interaction between the structure and the impacting process (Mazzorana et al., 2014). Intensity and process-related characteristics are often observed at monitoring stations in the channels and in the catchment but not at close range for every affected building. Moreover, the interaction of the building walls (or other structural elements) with the process itself depends on the direction of the flow, the percentage of sediment within the water, as well as the size of the material carried by the flow, but also on the wall material, physical and geometrical characteristics and condition of the affected structure. Since this information is rarely available from records of past events, laboratory experiments and numerical modelling are often used in order to determine the process intensity, the impact on the buildings and the reaction of the structure to the specific impact (Gems et al., 2016). These methods offer information that may substitute empirical data necessary for the derivation of vulnerability curves. A fair amount of studies used modelling techniques to understand and to simulate the impact of hazards on buildings for earthquakes and floods, but, for debris flow these studies are limited (Armanini and Scotton, 1993; Armanini et al., 2010; Scheidl et al., 2013; Mazzorana et al., 2014; Gems et al., 2016; Zhang et al., 2016). Some of these studies are also included in the specific review because they are essential for understanding the interaction between the elements at risk and the hazardous process.

1.3. Aim of the paper

Research on natural hazards generally, and specifically on debris flow, focuses primarily on hazard assessment, process modelling and mapping the extent of the flow as well as the development of mitigation and early warning systems. Nevertheless, it is understood that a thorough assessment of the physical vulnerability significantly improves risk analysis, supports decision making and enables practitioners to direct limited resources to the most vulnerable areas (Fuchs, 2009; Papathoma-Köhle et al., 2011). Moreover, the understanding, analysis and quantification of physical vulnerability supports cost benefit analyses (Holub and Fuchs, 2008) as well as risk assessment for future scenarios (Mazzorana et al., 2012). Finally, physical vulnerability