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Understanding impact dynamics on buildings caused by fluviatile sediment transport

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ABSTRACT

Understanding the impact dynamics on buildings caused by complex fluviatile sediment transport processes and the interaction with the exposed elements is still a major challenge. Especially flood hazards with large amount of mobilized sediments can cause severe damages to exposed building structures located within flood-prone torrential fans. Mitigation efforts, be they rooted in spatial planning or in local structural protection, may benefit from better insights into impact dynamics. In order to gain a better understanding of the interaction between torrential processes and buildings, a physical scale model was set up at a 1:30 scale to measure the impact forces on buildings and to comprehensively assess the determining factors. This model mirrors a part of the torrential fan of the Schnannerbach Torrent (Eastern European Alps, Austria). It includes its steep torrent channel and the adjacent floodplain, hosting complex building structures equipped with measurement devices on the wall elements to measure the three-dimensional impact forces of the torrential process. The experiments indicated that the impact forces depend mainly on the dynamics of the sediment deposition processes on the floodplain that are also influenced by the spatial distribution of the building structures, and less on the intensities of the analysed flood events and the grain size distributions of the transported and deposited sediments. The results of our study highlight the need to consider the interaction between the natural process and the built environment as well as the spatial distribution of buildings and their mutual interaction (shadowing vs. channelization) in flood risk management.

1. Introduction

Torrential fans are privileged settlement areas in many mountain regions of the world (Fuchs, 2009; Keiler and Fuchs, 2016). From a geomorphological perspective, however, these landforms are particularly dynamic (Stoffel et al., 2016; Slaymaker and Embleton-Hamann, 2018) because they are episodically affected by erosion, deposition and remobilization processes during extreme flood events (e.g., Costa, 1984; Crozier, 1999; Di Baldassarre et al., 2013; Mazzorana et al., 2015). As typical depositional systems, torrential fans result from a net difference between upstream and downstream solid discharges (Bull, 1977) and form basin outlets where rivers emerge from the constrained mountain area onto the plain (Clarke, 2015). They spread in a radiating pattern forming conical bodies having concave long profile and convex cross profile, starting from a single topographic apex (Clevis et al., 2003). Although net deposition prevails along the torrential fan formation, the distributary dynamics on its conical surface involve a variety of characteristic processes such as channel migration, channel avulsion, fan-head entrenchment and frequent switches between sheet and channelized flow (Cazanacli et al., 2002; De Haas et al., 2017) as a result of both allogenic (Hooke and Dorn, 1992; Guerit et al., 2014) and autogenic factors (Clarke et al., 2010; Muto et al., 2007; Ventra and Nichols, 2014).

The quantification of these processes on torrential fans, both with respect to space and time, is an essential requirement for subsequent risk mitigation since they may result in highly destructive mechanisms on building structures (Jakob et al., 2012; Kappes et al., 2012a, 2012b; Totschnig and Fuchs, 2013; Mazzorana et al., 2015; Zhang et al., 2016; Papathoma-Köhle et al., 2017; Simoni et al., 2017). Torrential processes involving large amounts of transported sediments range between debris flow and fluviatile sediment

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transport processes (Fuchs et al., 2008; ASI, 2009). Torrential processes are characterized by distinctive flow behaviour, a typical range of sediment concentration in the flow mixture and the event duration (Phillips and Davies, 1991; Iverson, 1997; Ancey, 2001; Tropea et al., 2007; Bergmeister et al., 2009). Debris flows are characterized by high sediment concentrations exceeding 40% to 50% by mass (Iverson, 1997; ASI, 2009; Bergmeister et al., 2009), mainly discharging in flow surges and therefore in short periods, whereas fluviatile sediment transport processes feature a more consecutive discharge with lower sediment concentrations less than 20% by volume (Bergmeister et al., 2009). Due to the variability in the process behaviour, the impact forces on obstacles in the flow vary significantly. A large number of studies (Vilajosana et al., 2007; Hübl and König, 2007; Proske et al., 2011; Scheidl et al., 2013) concentrate on the detection and measurement of debris flow impacts. Calculation approaches for the determination of the impact forces mainly focus on clear water conditions and debris flows (Bergmeister et al., 2009; Armanini et al., 2011) but earlier experimental studies on the dynamics of a debris flow surge on a vertical wall are also available (Armanini and Scotton, 1993; Armanini, 1997). Mainly two different mechanisms can be detected, characterized by the formation of a completely reflected wave and by the formation of a vertical bulge respectively. Jenkins et al. (2015) propose hydrodynamic pressures for the calculation of impacts of lahars on buildings as a function of the flow velocity and the flow density for further vulnerability analysis. Nevertheless, limited scientific attention has been devoted so far to the estimation of the impact forces of fluviatile sediment transport processes on obstacles, and as a result, vulnerability and risk assessment is regularly based on empirical relations between deposition height and degree of loss, neglecting any other process-specific characteristics (e.g., Fuchs et al., 2007; Akbas et al., 2009; Totschnig et al., 2011). To close this gap, in the present paper we focus on the impact forces of fluviatile sediment transport processes on buildings located on a torrential fan.

As far as confined channel flow is concerned through classical flume experiments, impact forces on single wall elements have been experimentally analysed in several studies (Armanini et al., 2011; Scheidl et al., 2013; Göttgens, 2016; Sturm et al., 2017a, 2017b). However, the experimental analysis of torrential impact forces in unconfined flow conditions on buildings, considering also the influence of surrounding buildings and material intrusion processes, is not available so far. This kind of research complimented with laboratory experiments is considered necessary in order to assess physical vulnerability of buildings (Fuchs et al., 2007). It is worth mentioning that experimental studies, such as the ones by Mignot and Riviere (2010), Guillen-Ludena et al. (2017), Riviere et al. (2017) and Sturm et al. (2017a) focused on the impacts at clear water conditions are available, whereas complex model set-ups for fluviatile sediment transport processes are still missing.

Furthermore, the major influencing parameters on the impact forces of fluviatile flood events on building structures still remain open. Spatial settlement characteristics such as settlement density, distances from the torrent, orientation of the exposed wall elements to the flow and the influence of surrounding buildings have recently been reported as important for the overall vulnerability assessment process (Fuchs et al., 2012). Moreover, surrounding obstacles may serve as local structural protection (Holub et al., 2012) for specific buildings, therefore, possible influences on the damage-generating impact forces of local protection measures should also be taken into account (Holub and Fuchs, 2009). In-depth knowledge on negative effects of local protection measures on different objects located further downstream, e.g. intensification of impact on other buildings, is important for land use planning strategies, hazard zone mapping and the design of flood protection of buildings and infrastructure (Eidsvig et al., 2017). Additionally, material intrusion in the building is a key factor for the resulting degree of loss (Mazzorana et al., 2014; Gems et al., 2016). In this respect, Mazzorana et al. (2014, 2015) and Gems et al. (2016) suggested that impact forces on the building envelope tend to decrease once the flow is penetrating through openings such as doors and windows. This impact reduction, however, is subordinated to the increase in the cost due to the loss of appliances, equipment, furniture and lethal threat to people caused by the intruding mixture of water and sediments.

Knowledge about the maximum impact forces of flood events on the exposed building is crucial for understanding specific damage patterns. Theoretically, load distributions and action combinations separate the resulting force in a hydrostatic, a hydrodynamic and an earth pressure component caused by sediment deposition (Mazzorana et al., 2014). Additionally, impacts from single boulders on the objects may be considered (Bergmeister et al., 2009; Mazzorana et al., 2014). However, for fluviatile sediment transport processes, it is still debated which of these forces is dominant.

So far, vulnerability analysis in the context of flood events and torrential hazards mainly focused on the vulnerability of individual building structures, based on empirical data. In more detail, vulnerability functions were developed using process characteristics such as the approaching flow heights or the deposition heights to estimate damages for every affected building without distinguishing the material of the buildings, the number of floors or the surroundings (Fuchs et al., 2007; Papathoma-Köhle et al., 2011; Papathoma-Köhle et al., 2012; Totschnig and Fuchs, 2013; Papathoma-Köhle et al., 2017). However, hazard impacts on individual wall elements are variable and further data and information is required to improve common vulnerability analyses (Papathoma-Köhle et al., 2017). Therefore, when referring to the impact forces representative for the flow processes, it is recommended that the buildings are divided into their wall elements which are further classified according to their location and orientation with respect to the torrent. However, quantitative data regarding these parameters throughout the flood event duration is scarcely available and estimated based on event documentation which further increases uncertainties.

Being inspired by previous efforts to experimentally explore the relationship between fan morphology and flood hazard assessment on alluvial fans (Zarn and Davies, 1994), the present study evaluates the potential of the physical-experimental approach to analyse the impact dynamics due to fluviatile sediment transport processes on buildings in a systematic way, outweighing the drawbacks of empirical statistical approaches in vulnerability assessment. More specifically, we aim at better understanding the influence of the flood event intensity parameters such as the discharge, the total sediment load and the sediment grain sizes on the impact forces. Further, we explore the way other special characteristics of the exposed settlements may affect the dynamics of the impact on selected buildings defined as target objects. We explicitly consider factors like settlement density, distance from the torrent, orientation of the exposed wall elements with respect to the flow or the influence of openings in the buildings envelope.

The present study is an effort to understand the interactions between the hazardous processes and elements at risk in order to support flood risk management efforts such as vulnerability assessment and decision making regarding local protection measures. The description of the model and the results of the study are presented in the following paragraphs. The model is based on the case study of Schnannerbach (Austria) which suffered significant losses during the 2005 flood event.

2. Case study

The flood events of August 2005 caused severe and widespread damages in the European Alps (Rudolf-Miklau et al., 2006; Fuchs et al., 2015). Many torrents mobilized large amounts of sediments triggered by heavy rainfall. Beside the high liquid and solid discharges, frequent process chains involving retrograding sediment