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Impact forces of torrential floods on exposed buildings

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Losses resulting from torrential processes are considerably high in mountain regions of Europe, in particular with respect to settlements located on torrential fans. Channel outbursts resulted in damage to exposed buildings repeatedly in the past which is conventionally expressed by vulnerability functions such as stage-damage functions. These functions provide a link between process magnitude and degree of loss, but have been so far established using empirical data from past events. Consequently, physical forces triggering damage remained unveiled, and only little is known on damage-generating flow velocities and pressures. To overcome this gap, we set up an experimental design on a 1:30 scale, including three buildings equipped with measurement devices on wall elements in order to detect triaxial impact forces, flow velocities and incidental flow heights. Specific hazard scenarios under clear-water conditions and with continuous bed-load supply were simulated, using variable grain size distributions. Results showed additional shadowing effects of surrounding buildings and significant influences of openings in the buildings envelope such as doors and windows. The study provides highly-valuable and physics-based information on the impacts of torrential hazards in mountain streams, and may be further used for calibration of conventional vulnerability functions but also for further development of existing vulnerability indices.

torrential hazards, vulnerability, exposure, impact, laboratory experiments

Силы воздействия селевых потоков на здания

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Убытки, вызванные селевыми процессами, высоки в горных регионах Европы. Особенно это касается поселений, расположенных на конусах выноса селей. Прорывы каналов в прошлом неоднократно приводили к повреждению подвергшихся воздействию зданий, которые условно выражаются функциями уязвимости, такими как стадии повреждения. Эти функции обеспечивают связь между величиной процесса и степенью потери, но до сих пор были установлены с использованием эмпирических данных прошлых событий. Следовательно, физические силы, вызывающие повреждение, оставались слабо изученными, и мало известно о скоростях и давлениях, создающих ущерб. Чтобы преодолеть этот пробел, мы создали экспериментальный проект в масштабе 1:30. В частности, были подготовлены три здания, оборудованные измерительными устройствами на элементах стен, для обнаружения трехосных ударных сил, скоростей потока и высот потока. Моделирование конкретных сценариев опасности в условиях чистой воды и с непрерывной подпиткой при загрузке с использованием переменных распределений размеров зерна. Результаты показали дополнительные эффекты затенения окружающих зданий и значительное влияние отверстий в оболочке зданий, таких как двери и окна. Исследование обеспечивает высокоценную и основанную на физических параметрах информацию о воздействии вихревых угроз в селевых потоках и может быть дополнительно использована для калибровки обычных функций уязвимости, а также для дальнейшего развития существующих индексов уязвимости.

селевая опасность, уязвимость, воздействие, лабораторные эксперименты

Introduction

Even though considerable efforts undertaken for the protection of settlements exposed to torrential hazards, significant losses have been recorded during the last decades in European mountain regions [*e.g., Fuchs et al., 2015; Fuchs et al., 2017a; Hilker et al., 2009*]. Flood discharge and sediment transport triggered by heavy rainfall and snow melt repeatedly leads to channel outburst and, consequently, to substantial damage to buildings [*Mazzorana et al., 2014*] and infrastructure [*Eidsvig et al., 2017*]. Due to climate change effects magnitude and frequency of such hazards is expected to increase [*Keiler et al., 2010*]. These changes together with socio economic changes will result in significant changes in the spatial pattern of exposure and risk on alluvial fans and in the valley floors [*Fuchs et al., 2017b; Röthlisberger et al., 2017*]. Recent research efforts on structural vulnerability of buildings were based on empirical relationships linking the degree of loss of individual buildings to the impact forces of torrential hazards [*e.g., Papathoma-Köhle et al., 2012a; Papathoma-Köhle et al., 2017; Totschnig and Fuchs, 2013; Totschnig et al., 2011*]. Resulting empirical vulnerability functions allow for the estimation of expected direct loss as a result of the hazard impact, based on a spatially explicit representation of process magnitudes and elements at risk. However, due to limitations of the available empirical data, information on the structural characteristics of affected buildings (e.g., material, design, etc.) are often not available [*Fuchs et al., 2007*], which reduces the predictive power of such vulnerability functions [*Papathoma-Köhle et al., 2011*]. To close this gap, process-structure interactions in an experimental setup may be considered as an alternative approach since real-scale data are so far hardly available.

Although the impact forces of torrential hazards are the relevant trigger for building damage, their measurement and computation still remain challenging [*Mazzorana et al., 2014*]. Therefore, proxy data such as the approaching flow heights or flow velocities were mainly used to assess the potential vulnerability of exposed buildings [*Papathoma-Köhle et al., 2017*]. To overcome these challenges, *Quan Luna et al.* [*2011*] were using numerical back-calculation for flow heights and impact pressure. *Fuchs et al*. [*2015*] suggest that the impact forces of fluviatile sediment transport with sediment concentrations less than 20% and, compared to debris flows, longer durations are very much different than debris flow impacts although this has not been statistically proven. In contrast, research on the impacts of clear water is more advanced, even though the model set-up to determine the impact forces has been kept rather simple [*Armanini et al., 2011; Mignot and Riviere, 2010; Riviere et al., 2017*]. Further studies report equations to quantify the impact of sediment transport processes, and in particular debris flow hazards [*Scheidl et al., 2013*]. However, such approaches fail to provide highly accurate and precise results with respect to the complex three-dimensional flow behaviour of sediment transport observed [*Gems et al., 2016*]. Hence, there is an apparent need to study process-structure interactions for torrential hazards in an experimental setup using physical scale models since real-scale data are not available. Our study contributes to close this gap, which will allow to improve the design of buildings in hazard areas [*Holub et al., 2012*], to support efforts for the assessment of physical vulnerability, and to highlight the need of local adaptation measures [*Holub and Fuchs*, *2008*]. Furthermore, the results of our study may be used to validate and improve existing empirical vulnerability functions for torrential hazards.

Methods

A physical scale model was set up, representing the Schnannerbach torrential fan located in western Austria in the Eastern European Alps. The torrent channel is characterized by a sequence of artificial steps and pools and a mean gradient of about 13 %. The fan includes major part of the village of Schnann, and recent flood events in 1999, 2002 and 2005 relocated large amounts of sediment from the headwaters (6.3 km^2) to the confluence with the receiving water [*Rosanna river, Rudolf-Miklau et al., 2006*]. Especially the well-documented flood event from August 2005 led to substantial damages in the village, with a reported loss of € 403,000 [*Totschnig et al., 2011*]. This event was used as a model proxy since valuable data and information on the process characteristics were available [*Kammerlander et al., 2016*].

Our study focused on the impacts on three specific buildings in the case study area (Fig. 1). The scaled construction of the buildings was based on quasi-natural conditions achieved using photogrammetry. They were equipped with 16 force sensors to record three-axial pressure forces with a high temporal resolution of 200 Hz on every equipped wall element and appropriate measurement amplifiers (both manufactured by ME-measuring systems) on the torrent-facing wall elements (Fig. 2). Measuring voltages induced by the approaching loads were converted to forces by means of a calibrated relation of the values. The impact force devices were attached to a rigid framework inside the building and were insensitive to eccentric load applications. The wall elements were freely movable in order to avoid mutual interaction and the transmission of the impact forces to the bottom of the scale model. The gaps between the wall elements themselves and the bottom were masked with thin plastic films to avoid sediment getting stuck in these gaps and potentially distorting the measured impact forces. The remaining buildings of the settlement were not equipped with measurement devices but were considered as surrounding buildings, which potentially influence the process and impact patterns at the three equipped buildings. Surrounding buildings were constructed as rigid blocks without any openings.

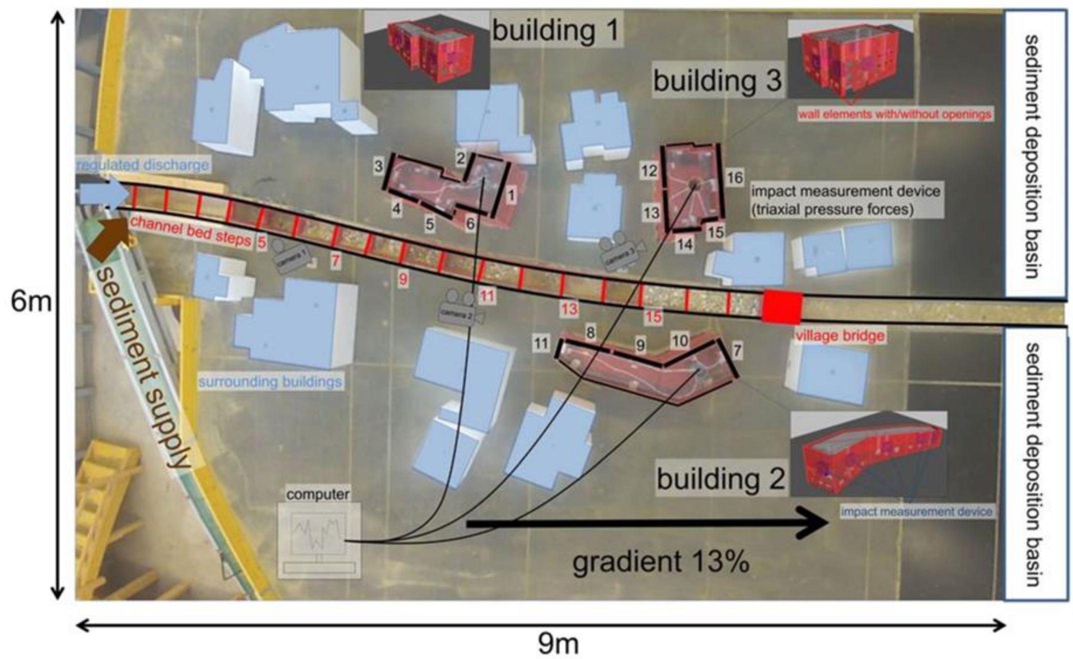

Fig. 1. Overview on the components of the Schnannerbach scale model. Source: *Sturm et al.* [in press-a]

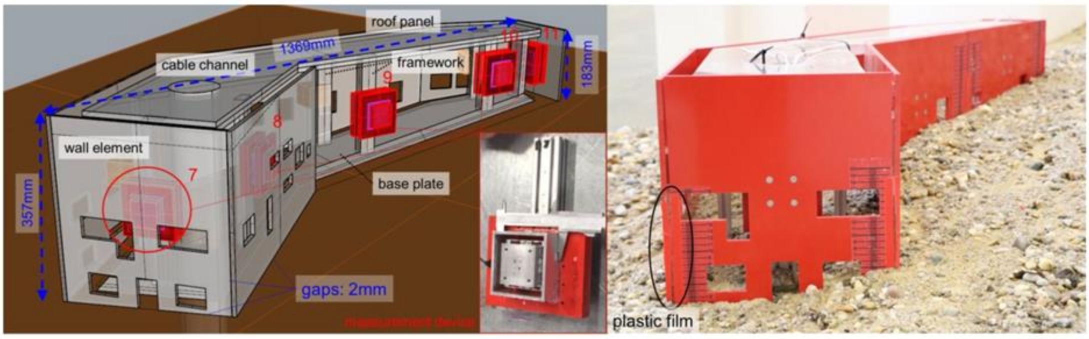

Fig. 2. 3D-model of building #2 with main components (left) and picture of building #2 after an experiment with deposited sediments (right); model dimensions. Source: *Sturm et al.* [in press-a]

For determining the impacts of sediment transport processes on the buildings the sediment was supplied continuously with a conveyor belt to the channel at the upper model boundary. Two grain size distributions were used for the supply of sediments. They consisted of different grain classes of quartz gravel and sand each, and were strongly related to the field samples at different locations in the Schnannerbach torrent. In order to avoid suspended load transport behaviour and cohesion effects in the experiments, the minimum grain size in the experiments was set to 0.5 mm (0.015 m in prototype dimensions). The bed of the model channel was filled with bed-load, and to take the roughness of the stonewalled channel into account, a structure was carved into the wall element surfaces according to the joints of the stone layers. To represent the average roughness of the overland flow areas properly, the terrain outside of the channel was uniformly covered with 0.5 mm diameter sands (0.015 m in prototype dimensions).

Flow velocities of the water surface were measured with PIV methods [*Thieleke and Stamhuis, 2014*]. Therefore, swimming tracers were added flatly to the water and flow paths were detected using cameras from top view. Defining time steps between the individual video frames and measuring distances on the water surface allowed us for an estimation of the surface flow velocities. The impacting flow heights at the wall elements as well as the deposition heights around the buildings were measured for all experiments by use of water gauges printed on the wall elements. One camera was recording the experiments from top view and three cameras, each focusing on one of the three equipped buildings, supported the documentation of the experiments.

The experimental program included clear water experiments and experiments with continuous sediment supply. While clear water discharges in the torrent channel did neither exceed channel capacity, nor reach the volume of the 1-in-150-year design flood [30 m^3 s-1 in nature according to *Rudolf-Miklau et al. 2006*], specific overtopping points in the channel were defined and equipped with mobile closure devices. These different overtopping points lead to a considerable variety of impacts on the buildings relating to spatial dispersal and variable impact angles on the wall elements.

To analyse the system under sediment-laden conditions in accordance with the observed flood events characterised by overtopping of the channel due to regressive deposition, different scenarios were studied. For those experiments, the assumed initial condition was a blockage of the channel cross section at the village bridge (Fig. 1). Through the regressive deposition, all buildings were affected by the hazard process during each of the scenarios. A total of 120 clear water experiments and 20 sediment experiments was conducted with different discharges, different grain size distributions and sediment loads. Almost steady-state discharge was set for all experiments. Minor changes in the transport capacity of the channel due to the observed sediment depositions and corresponding dynamics in the flow behaviour led to necessary, small adjustments of the discharge during the sediment experiments. Although clear water conditions showed a steady-state condition at every spot within the model for each of the experiments, sediment transport and deposition processes led to temporarily variable conditions in the torrent channel and on the torrential fan, despite the steady-state conditions at the upstream model boundary [*Gems et al., 2014*].

To determine the influence of discharge passing through the interior of the buildings, openings in the building envelopes were considered in specific experimental scenarios. Comparison of hazard scenarios with and without the influence of surrounding buildings on the impact forces enabled the quantification of the influences of the settlement structure on the impact forces.

Results and Discussion

The results from the scaled model are presented in real-scale dimensions. In order to provide comparable and transferable modelling results the measured forces on wall elements with different widths are converted to a normal wall element with the width of 1 m. The presented results in this paper focus on the specific normal forces, although three-dimensional forces were measured. The measured shear forces on the wall elements were significantly lower than the normal forces and were thus not relevant for possible damages.

Clear water experiments

Clear water modelling results for one specific experimental model layout are shown in Fig. 3 in terms of mean values and standard deviations using boxplots [*Sturm et al., in press-a; b*]. The spatial pattern of flow velocities on the approached walls was clearly demonstrated; and the three shown velocity patterns prove increasing flow velocities with increasing discharges, leading to increasing impact forces on the exposed wall elements. As a result of the directly approaching discharge, walls #3 and 11 (building # 1 and 2, respectively, cf. Fig. 1) showed the highest impacts. Despite walls #12 and 13, all other elements were only marginally affected during this specific experiment. In general, our 120 experiments with clear water discharge clearly showed that parameters such as flow velocities and flow heights, but also approaching flow angles and shadowing effects between buildings (as shown in Fig. 3 for building #3) affect the impact forces on the exposed buildings, and in particular flow heights were in good accordance with the impact forces, as given in Fig. 4 for the entire set of experiments. The resulting regression is given in Equation (1), where f is the specific normal force in kN m^{-1}, and h is the approaching flow height in m.

$$f = 1.01145 \cdot h + 3.35613 \cdot h^2 \quad (1)$$

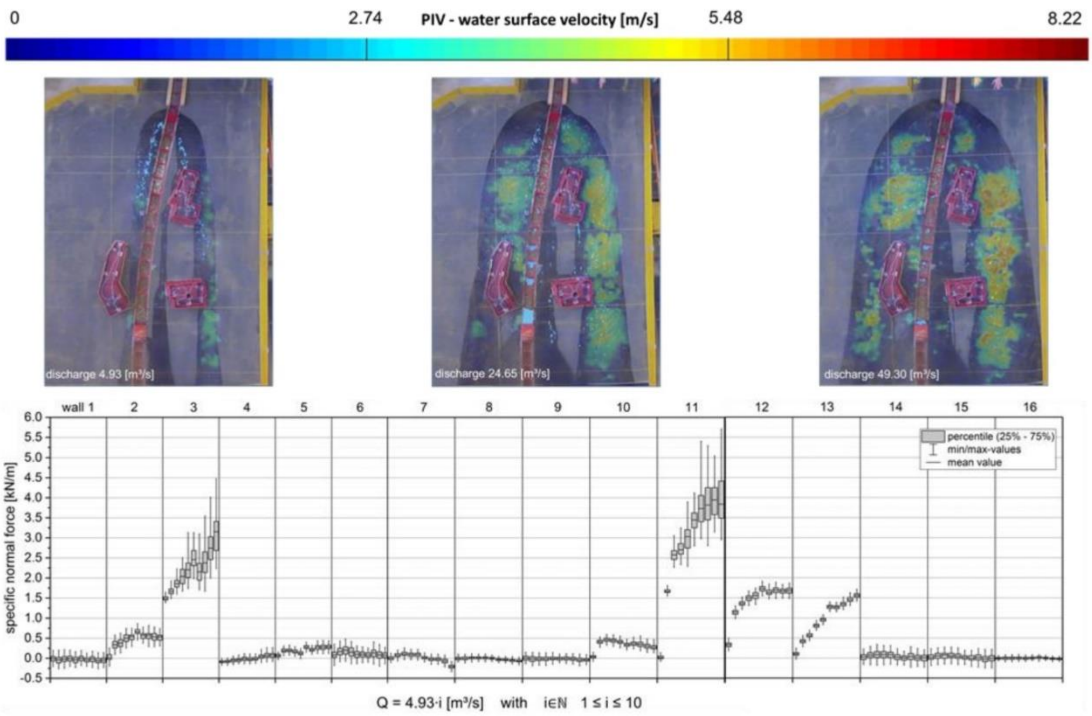

Fig. 3. Specific normal forces and water surface velocities for one specific model layout (without surrounding buildings; without openings in the wall elements); wall elements and channel bed steps according Fig. 1; prototype dimensions. Source: *Sturm et al.* [in press-a].

Experiments with sediment transport

The 20 experiments with sediment supply to the flume showed no significantly different deposition behavior on the fan if discharge, sediment concentration or grain sizes were varied. Instead, the impact on the building envelope was mainly triggered by already existing sediment depositions on the fan, leading to different flow paths on the floodplain and, consequently, to different impact forces [*Sturm et al., in press-a; b*]. In particular because of the regressive deposition observed in the channel, channel outburst was spatially highly variable and impacts on the different wall elements showed a higher variation than during clear water experiments. Moreover, the intrusion of material through the building openings led to an additional impact on the wall elements, but from the inner side of the buildings. The experiments also revealed that the highest impact forces were not necessarily during the timestep when a wall was first hit by the sediment-water mixture, but during the subsequent timesteps when material was already starting to be deposited at the building envelope. Moreover, when material deposits in the channel or on the floodplain directed the flow towards a wall element, the measures forces increased due to the resulting higher specific discharge. The results of the experiments with sediment supply are summarized in Fig. 5.

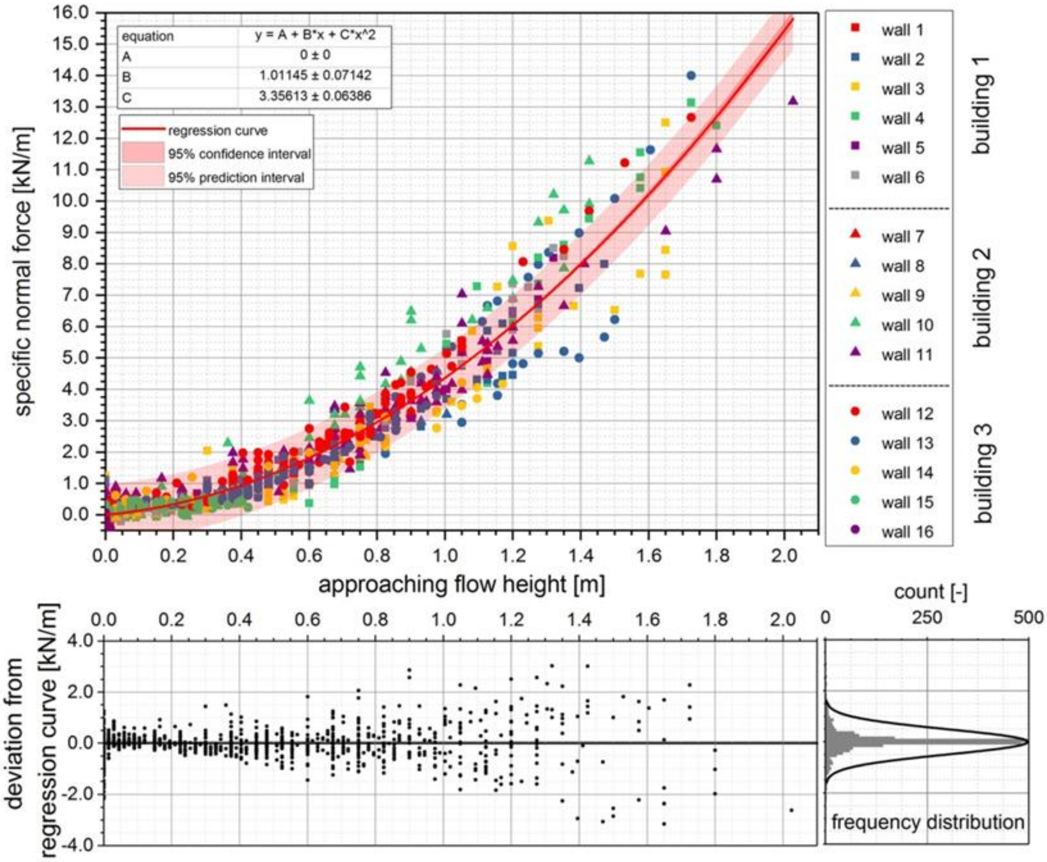

Fig. 4. Correlation of approaching flow heights and specific normal forces for all clear water experiments; prototype dimensions. Source: *Sturm et al.* [in press-a]

Because of the higher variation in comparison to the clear water experiments, the overall spread in the data is higher, resulting in a considerably spread confidence interval. The resulting regression is given in Equation (2), where f is the specific normal force in kN m^{-1}, and h is the approaching flow height in m.

$$f = 4.47492 \cdot h + 2.29447 \cdot h^2 \quad (2)$$

Discussion

In mountain hazard risk management, the assessment of the structural vulnerability of buildings exposed to torrential flooding is an important and challenging task. While in recent years, multiple approaches using empirical vulnerability functions [*e.g., Papathoma-Köhle et al., 2012b; Totschnig and Fuchs, 2013; Totschnig et al., 2011*], matrices [*e.g., Hu et al., 2012; Zanchetta et al., 2004*] and indicators [*e.g., Ettinger et al., 2016; Papathoma-Köhle, 2016*] has been published and discussed as appropriate method to increase the overall explanatory power of risk assessments, the still missing information on the interaction between elements at risk and the hazard process has been widely debated yet not sufficiently enough studied in order to provide necessary information to be used in operational hazard and risk mitigation [*Mazzorana et al., 2014; Papathoma-Köhle et al., 2017*].

The conducted scaled experiments in the Schnannerbach model provided insights in these interactions. The experiments clearly showed how impact forces during torrential flood events develop, as well as the interaction between elements at risk located on the fan and the impact forces on adjacent buildings. As shown in Fig. 5 by the blue line, impacting forces of the water-sediment-mixture are higher than those of the clear water experiments, especially at higher approaching flow heights. The fluctuation of the forces and the maximum impact forces are much higher during sediment loaded discharges. Moreover, a clear relation between approaching flow heights and specific impact pressures was measured both, for clear water and sediment discharge. This can be used to assess the accuracy of existing empirical equations using flow height as one of the input parameters in vulnerability assessment.

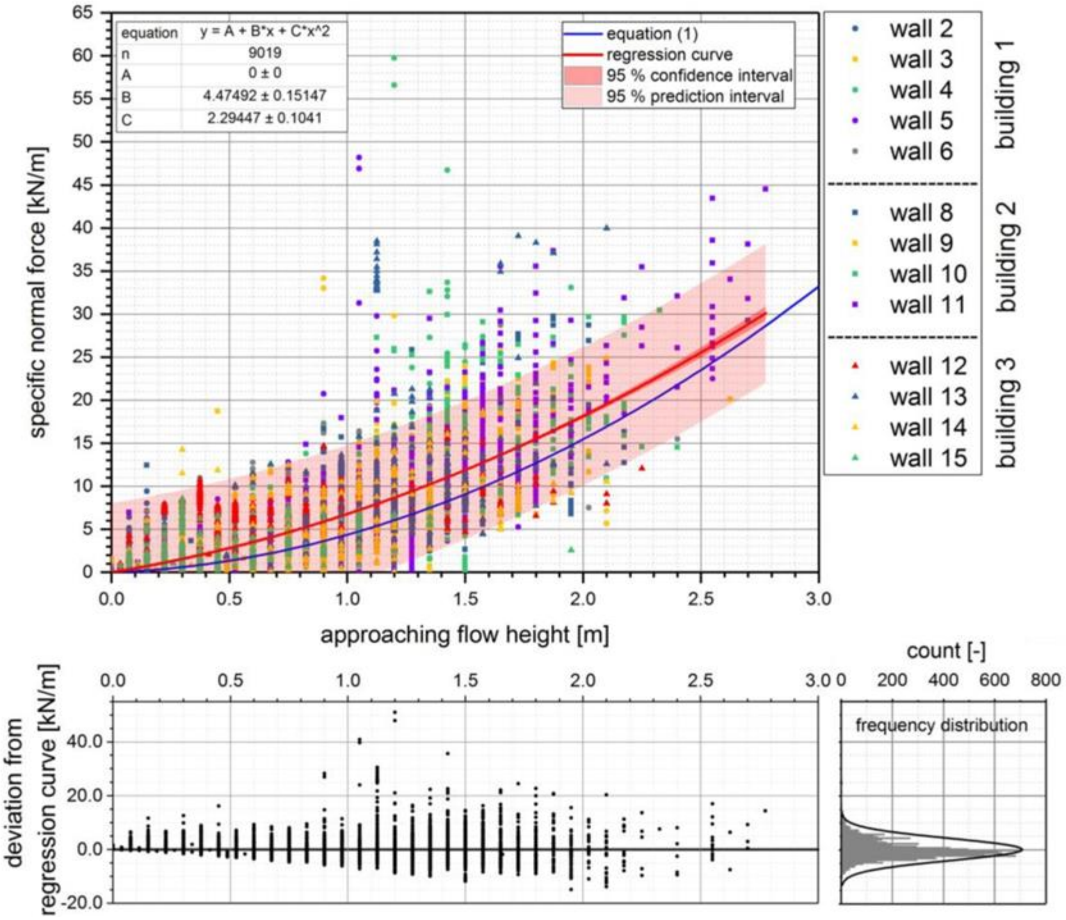

Fig. 5. Correlation of approaching flow heights and specific normal forces for all experiments with sediment supply; prototype dimensions. Please note that approaching flow height is defined as the sum of deposition height and the height of the overflowing liquid-solid mixture. Source: *Sturm et al.* [in press-a]

Main limitations for a wider applicability of the results are related to the scaling of the model and a corresponding limitation of possible gain size distributions, even if the model was calibrated using the August 2005 flood event [*Gems et al., 2014*].

Nevertheless, the study is one of the few studies in the literature using laboratory experiments and scale models to investigate the interaction between buildings and torrential hazards, and is therefore of vital importance for vulnerability research. Apart from the validation of empirical vulnerability models outlined above, the results may support the ongoing efforts in the development of vulnerability indicators to be used in mountain hazard risk management [*Papathoma-Köhle et al., 2017*]. Moreover, the approach can be adopted in building retrofitting and land use planning in order to arrive at more resilient mountain societies, one of the goals specified in the Sendai Framework for Disaster Risk Reduction [*Zimmermann and Keiler, 2015*].

The proposed model can be further developed in order to approach further gaps recently identified in mountain hazard risk management [*Papathoma-Köhle et al., 2017; Sturm et al., in press-a*], including the role of openings such as doors and windows, exploring the behavior of the overall building under time-varying impact loads, and defining also other types of limit states and the economic implications of structural flood damages [*Milanesi et al., in press*]. In parallel, the method presented feeds into ongoing discussions in socio-hydrology, in particular with respect to the socio-economic impacts of hydrological hazards and their consideration in risk assessment [*Di Baldassarre et al., 2015; Fuchs et al., 2017c*].

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