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Debris flow: its intensity and damage caused to the built environment

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Debris flow events are known today as one of the most dangerous natural hazard events due to the elevated impact pressures they can reach. Depending on its intensity, a debris flow has the capacity to flatten forests and carry along the tree trunks, to completely demolish buildings and consequently to create a great risk to human life.
However, the damage caused to a building by a debris flow also depends on the structural resistance of the building, orchestrated by many other indicators such as the construction material, the number of floors, the orientation of the building, the maintenance levels, etc. As a result, a historical survey was conducted in this work, studying the different types of building structures and the damage they suffered due to debris flows. Furthermore, the damage to the buildings as such is a parameter that can be assessed by various methods. What is certain is that the higher the intensity of the debris flow, the greater the damage to the built environment and thus the greater the risk to human life.
In order to understand better this natural process and reduce the risk of human and economic losses a large amount of research has been done in the field regarding the process of debris flow itself. Nevertheless, the assessment of debris flow intensity remains a task quite difficult to accomplish. The latter is due to various reasons; for instance, on one hand, there is the versatility of debris flow in terms of the origins of the materials that compose it, the height and velocity it can reach and on the other hand, the difficulty of determining these parameters. These challenges have been at the origin of many different approaches developed and used throughout the years in order to assess debris flow intensity. In this paper some of the existing approaches established in the quest of debris flow intensity assessment will be presented and evaluated.
The main objectives of this paper are first the definition of the main types of structures vulnerable to debris flows, then the suggestion of a methodology to assess the damage caused to buildings by a debris flow and finally the proposal of a general approach, commonly implementable, for the assessment of the intensity of debris flows.
Keywords: Debris flow; Building vulnerability; Building damage; Impact pressure.

1. Introduction

Debris flow events are amongst the most dangerous natural hazards, powerful and destructive, with the ability to move large volumes of debris and destroy infrastructure. They have caused a lot of damage to the built environment throughout the years and represent a great risk to the human life.

The United States Geological Survey has classified debris flow as one of the most dangerous natural hazards in terms of loss of life. According to Takahashi (1981), in Japan, debris flow events cause about 90 deaths each year.

Most recently, Casey A. Dowling and Paul M. Santi (2013) conducted a study analyzing debris flow fatalities in the period from 1950 to 2011. In this study were analyzed 213 events of debris flow that occurred in 38 countries around the world. The number of fatalities recorded in these events is 77'779. This study concluded that debris flows kills at least a median of 165 persons annually worldwide, the median number of people killed in fatal debris flow per event according to this study is 11.

According to the Federal Office for the Environment (FOEN), between 1972 and 2018, natural hazards (floods, debris flows, landslides and stone and rock fall process) manifested in Switzerland caused approximately 305 million francs of damage per year. Regarding the material damage caused, more than 90% is due to floods and debris flows, 10% to landslides. Surveys made by the Federal Institute for Forest, Snow and Landscape Research (WSL) showed that four out of five municipalities have suffered damage from debris flow or flooding in the past 45 years.

Climate change and the intensified use of land, not adapted to natural hazards, only increase the risk associated with them. As a result, an increase in the frequency and intensity of natural disasters is to be expected in the years to come. Since debris flows are considered one of the most dangerous natural hazards, it is more important now than ever to properly study and understand this natural phenomenon, so as to assess the intensity it can reach and the damage it can cause.

To this end, in this article we will define the main types of structures vulnerable to debris flows, based on a historical survey carried out in this study. Then, we will propose a methodology for assessing the damage caused to buildings by debris flows and lastly, we will propose a general approach, which may be widely implemented, for the evaluation of debris flow intensity.

1.1. Debris flow classification

Depending on their composition, debris flow can be classified into two categories:

1. Muddy debris flow: contains a large fraction of fine particles (<40 mm), which when mixed with water, form a muddy mass. The large particles can be considered as dispersed in this muddy mixture, with little to no contact between them. Therefore, the relative movements between the particles are quite lubricated, dictating the behavior of the entire mixture. Deposits of this type of debris flow have a regular, rounded shape in the direction of flow.
2. Granular debris flow: contains a high concentration of large particles, with a low fraction of fine ones. As a result, contacts between the grains during a flow are easy and numerous. The deposits of this type of debris flow have an irregular shape, with edges similar to those of a sand pile.

Granular debris flows are more dangerous than muddy debris flows because their fronts contain large boulders and rocks, resulting in higher velocities and greater destructive force.

In this study, we will only be interested in the impacts of granular debris flow on buildings.

2. Debris flow in history

A historical study of past events of natural hazards is necessary and very useful mainly in two areas:

1. Study of phenomena: the analysis of past events allows us to become familiar with the various natural hazards. Thanks to records and investigation of past events, we have been able to determine most of the properties of diverse natural hazards.
2. Future land use planning: with the aim of determining the different danger zones and the protective measures that must be put in place.

The historical study conducted in this paper covers four major debris flow events in Switzerland and France, two in Italy and three major events in the world (Venezuela, China and South Korea). For each event, information was collected on the characteristics of the debris flows (height, volume, velocity; if available), the construction materials and the damage caused by the event. The main goal of this study is to become familiar with the typology of affected buildings and the damage they suffered during past debris flow events.

Table 1 shows the physical characteristics of the 13 debris flow disasters, the construction materials of the buildings as well as the damages caused.

3. Types of building structures

In this section are categorized the different types of building structures retrieved from the historical survey made in this study. The different categories are obtained first on the basis of the type of structures and then in dependence of the construction materials and the number of stores.

Among the various structures affected, we very often find chalets – rural buildings in mountain regions, the essential construction material of which is wood (whose main building material is wood). The other types of structures observed are masonry and reinforced concrete villas, industrial halls and multi-storey apartment buildings.

As presented in Table 2, four main building types were catalogued in this work: chalet, individual villa, industrial building and residential building. Each of these is subdivided into several categories based on the construction material and the number of floors.

For example, the observed individual villas affected by debris flow were most often built of masonry or reinforced concrete and were between two and three stories high – this will give us a total of four categories of structures:

1. Two-story masonry individual villa;
2. Three-story masonry individual villa;
3. Two-story reinforced concrete individual villa;
4. Three-story reinforced concrete individual villa.

4. Debris flow building damage assessement

The damage that an element at risk can suffer from debris flow depends on various factors. The two main determinants of the degree of damage to structures are the intensity of the debris flow and the structural strength of the exposed object.

The structural strength of the exposed object itself depends on several factors, among which: the construction material, the height / floors of the building, the age of the building, the mitigation measures, the orientation of the building, the regularity in building elevation etc.

Each construction material has a different structural resistance to the impact of debris flow. In comparison with reinforced concrete buildings, masonry buildings have very low resistance to horizontal thrust. As a result, reinforced concrete buildings can withstand much greater debris flow impacts than masonry buildings.

In the studies made by Hu *et al*. (2012) and Kang *et al*. (2016), it was illustrated through examples

Tab. I – Historical survey recapitulation.

Chronological recapitulation of the historical study on past debris flow events						
Place	Date(s)	Height [m]	Velocity [m/s]	Volume [m³]	Construction materials	Damages caused to the built environment
Verdun, France	24.06.1875	-	-	100'000	Masonry	- 30 buildings completely ruined; - 15 buildings with major damages.
Modane, France	25.08.1987	0.5 to 1.0	-	80'000	Steel	- 16 buildings ruined or seriously damaged; - 7 ground floors and cellars et 75 garages et cellars flooded.
Martello, Italy	08.1987	1.2-3.0	-	-	Masonry	- Several buildings completely ruined; - Many buildings with major damages.
Sarno, Italy	05.05.1998 06.05.1998	2.0	2 to 5	-	Masonry	- 150 buildings completely ruined; - 500 buildings gravely damaged.
Vargas, Venezuela	15.12.1999	0.5 to 6.0	-	1.8 million	Masonry Reinforced concrete	- 23'000 buildings completely ruined; - 42'000 buildings gravely damaged.
Grimentz (VS), Switzerland	12.05.1999	2.0	-	11'000	Ground floor in reinforced concrete, upper floors in wood	- Significant structural damage; - Translation of the structure;
Schans (GR), Switzerland	11.2002	-	-	50'000	Ground floor in reinforced concrete, upper floors in wood	- Many buildings seriously damaged or entirely ruined.
Brienz (BE), Switzerland	23.08.2005	2.5 to 4.0	6 to 10	70'000	Reinforced concrete Masonry Wood	- 48 buildings completely ruined; - More than 200 buildings damaged, with damages ranking from severe to mild.
Domène, France	23.08.2005	2.0	-	-	Masonry Reinforced concrete	- 70 buildings seriously damaged.
Zhouqu, China	07.08.2010	6.0 to 9.0	11	-	Masonry Reinforced concrete	- 33 buildings completely ruined; - 20 buildings with major damage.
South Korea	07.08.2011	0.4 to 5.8	1 to 8.5	-	Masonry Reinforced concrete Wood	- Many buildings have suffered major structural damage,
Modane, France	01.08.2014	0.5 to 2.0		40'000-60'000	Steel	- 13 industrial buildings et 1 house damaged.
Bondo (GR), Switzerland	23.08.2017	1.0 to 2.5	-	220'000	Masonry Reinforced concrete	- 13 buildings completely ruined; - Hundreds of buildings gravely damaged.

of real events that for the same debris flow intensity, depending on the construction material, the damage to buildings is not of the same degree.

Thus, according to the study by Kang *et al*. (2016), for an impact pressure of less than 35 [kPa], reinforced concrete buildings suffer only minor damage. On the contrary, under an impact pressure of between 15 and 30 [kPa] masonry and wooden buildings suffer major structural damage. It was determined in this study that an impact pressure greater than 100 [kPa] is required for a reinforced concrete building to suffer major structural damage.

In the study by Hu *et al*. (2012), the authors established two types of structures according to the construction material: reinforced concrete buildings and concrete brick buildings. For reinforced concrete constructions, they obtained that the latter undergo major structural damage when the impact pressure is greater than 110 [kPa].

Then, in the study by Zanchetta *et al*. (2004), the authors established damage classes independently of the typology of the structures, depending on the impact pressure. According to their classification, under an impact pressure greater than 90 [kPa], all buildings are completely destroyed.

All of the above-mentioned approaches classify the damage caused to a building during debris flow event based on the impact pressure.

In this study we use another approach in order to assess the damage to buildings, regardless of the impact pressure of debris flow; classification of the damage

Tab. 2 – Brochure of the different types of vulnerable structures considered in this work.

Brochure: Types of vulnerable structures				
N°	Construction type	N°	Construction material(s)	Number of stories
1	Chalet	1.1	Wood	1
		1.2	First floor in concrete, upper floors in timber	2-3
2	Individual villa	2.1	Masonry	2-3
		2.2	Reinforced concrete	2-3
3	Industrial building	3.1	Steel	3
		3.2	Wood	3
4	Residential building	4.1	Masonry	≥ 3
		4.2	Wood	≥ 3
		4.3	Reinforced concrete	≥ 3

in order of severity. This approach defines the different damage classes according to the percentage of damage suffered by the element at risk (also applied by Jakob *et al*. (2011)). The proposition of building damage evaluation in this work is presented on Table 3.

5. Debris flow intensity

Unfortunately, natural hazard events are often poorly documented. With regard to debris flow, a large number of parameters are generally lacking preventing us to carry out an effective assessment of the building's vulnerability to these events. There are cases when the information necessary for the calculation of the major parameters is available, but quite rarely. On the other hand, the height of the debris flow at the point of impact can be estimated easily and with a small margin of error. Consequently, in the current available literature, there are several studies that link the intensity of debris flow to a single parameter: the height of the deposits.

This first simplified approach for determining the intensity of the hazard has been used in several studies carried out on the vulnerability of buildings to debris flow (Fuchs *et al*. (2007), Akbas *et al*. (2009), Tsao *et al*. (2010), Lo *et al*. (2012), Papathoma-Köhole *et al*. (2012), Totsching and Fuchs (2012), Ciurean *et al*. (2016)).

However, in the study made by Li *et al*. (2010), in addition to its height the authors proposed to take flow velocity into consideration when estimating the intensity of debris flow. This observation was also made by Papathoma-Köhole *et al*. (2012) where the authors pointed out that other parameters, apart from debris flow height, such as debris flow velocity and impact pressure, must be taken into consideration for a more cautious estimate of the intensity.

The study by Jacob *et al*. (2011), is one of the very few where the intensity of the phenomenon was determined as a function of the flow velocity and the maximum height at the point of impact. In order to evaluate the intensity of the debris flow, this study employed the equation (1.2) presented in Table 4.

So as to be able to assess the intensity of a debris flow more accurately, it is necessary to establish the velocity of the debris flow alongside its height. Determining the latter is difficult but not impossible.

In some cases where surveillance measures have been put in place, velocity can be measured or estimated from high-speed videos. In the absence of monitoring measures, the speed of the debris flow can be calculated.

Several equations proposed for such a calculation can be found in the available literature. Equations (2.1) by Chow and (2.2) by Wigmosta, presented in Table 5, are based

Tab. 3 – Damage classification defined in the present study.

Damage class	Description	% damage to the entire structure
I. Sedimentation	The load-bearing elements of the building are not affected and the stability of the building is not impacted. The damage to the building consists in sedimentation and damage to the windows and doors. Therefore, no major intervention is necessary.	< 20
II. Minor structural damages	A minor part of the load-bearing structure is affected, but the damage caused is repairable and does not require urgent intervention. The debris flow has entered the building causing damage to the indoor walls.	20-50
III. Major structural damages	Major damage to the walls and supporting columns of the building. Urgent reconstruction of the damaged structural parts is necessary. The affected parts are repairable; however, the repair costs are likely to be very high. An evaluation is necessary in order to decide whether a total reconstruction might be a better solution. An evacuation has to be carried out.	50-80
IV. Total collapse	The building is totally destroyed or has suffered unrepairable damage to the load-bearing structure. The building must be completely rebuilt.	> 80

on the observed ruins on the buildings. They are based on the height of the debris flow at the point of impact and take into consideration the height of the debris flow at the point of impact. Equation (2.3), proposed by Rickenmann, includes the slope of the channel and the volume of the debris flow.

Regardless of the approach chosen/available for the determination of velocity, there will always be a considerable margin of error in the values obtained. Consequently, this margin of error must be accounted for in the results obtained for the intensity of the hazard and then will also be reflected in the estimation of the vulnerability of the building which is a function of the intensity; this may produce significant deviations in the final results of the vulnerability assessment.

The Swiss Association of Cantonal Fire Insurance Institutions (VKF) has taken a different approach from the previous two in defining the intensity of debris flows. They have classified the intensity of debris flows based on their height and/or their velocity. The classification established by the VKF is presented on Table 6.

The disadvantage of this classification is the lack of representative values. As already mentioned earlier and according to the short historical study carried out in this paper, debris flows can reach high velocities and heights. Some values of these two parameters are presented in Tables 7 and 8.

All the approaches mentioned so far are different in the choice or application of parameters, nevertheless they all revolve around two parameters: the height and/or the velocity of the debris flow. These are the two most commonly used parameters to determinate the intensity of debris flow.

Still, an important remark to make regarding this phenomenon is that for the same height, two debris flows can have different flow velocities and vice versa. This is primarily due to the materials that make up the debris flow. Depending on the location of origin, the geological and geomorphological characteristics of the materials can vary greatly from one debris flow to another and thereby affect the density of the debris flow. This leads us to the conclusion that to effectively determine the intensity of a debris flow, we cannot rely solely on its height and flow velocity disregarding its density.

The intensity of the debris flow correlates with the damage to buildings; in general, the higher the intensity of the debris flow, the greater the damage caused. The damage caused by a debris flow on a building depends on the impact pressure that the debris flow exerts on the building which can be correlated with debris flow density. Impact pressure could therefore prove be an interesting parameter to assess the debris flows intensity. This point was also raised in studies conducted by Papathoma-Köhole *et al*. (2012) and Kang *et al*. (2016).

The impact pressure of a debris flow consists of three components:
1. Static pressure;
2. Dynamic pressure;
3. Static replacement pressure (due to impact force).

In the study by Kang *et al*. (2016), the intensity was determined as a function of three parameters: the velocity, the height and the impact pressure of the debris flow. The relation used for the calculation of the impact pressure is the one proposed by Zanchetta *et al*. (2004):

$$P_t = \frac{1}{2}\rho_{df} g h + \rho_{df} v^2 \qquad (3)$$

with ρ_{df}: debris flow density
v: debris flow velocity
h: debris flow height

The three main parameters used in equation (3) for calculating the impact pressure, the velocity, height and density of debris flow should be estimated or if possible calculated.

Concerning the density of de-

Tab. 4 - Existing equations for debris flow intensity evaluation.

Equation	Parameters	Author	Equation number
$I = 0.1\ D_{dpt}$	D_{dpt}: deposit height measured in cm	Li *et al.* (2010)	(1.1)
$I_{DF} = dv^2$	d: height of the debris flow at the point of impact v: velocity of the debris flow at the point of impact	Jacob *et al.* (2011)	(1.2)

Tab. 5 – Existing equations for debris flow velocity evaluation.

Equation	Parameters	Author	Equation number
$v = (2g\Delta h)^{0.5}$	g: gravitational acceleration	Chow (1959)	(2.1)
$v = (1.21g\Delta h)^{0.5}$	Δh: height of the debris flow	Wigmosta (1983)	(2.2)
$v = 2.1Q^{0.33}S^{0.33}$	Q: peak discharge S: channel slope	Rickenmann (1999)	(2.3)

Tab. 6 – Evaluation of debris flow intensity according to VKF.

Intensity		Height of the debris flow h_f [m]		Velocity of the debris flow v_f [m/s]
0	Zero	0	Or	0
1	Low	Doesn't exist	Or	Doesn't exist
2	Medium	≤ 1	Or	≤ 1
3	High	> 1	And	>1

bris flows, it generally ranges from 1'500 to 2'500 [kg/m^3], or more precisely, as illustrated by several studies (Curry 1966; Okuda *et al*. 1980; Li and Luo 1981; Pierson 1981, 1985; Li *et al*. 1983; Zhang 1993; Iverson 1997; Hu *et al*. 2012), from 2'000 to 2'200 [kg/m^3]. Different assessment method was applied by the VKF, who assigned a specific density per type of debris flow. Thus, according to their recommendations, muddy debris flows have a density of 1'800 [kg/m^3] and granular debris flows a density of 2'200 [kg/m^3].

The inconvenience of equation (3) is that it omits the pressure due to the impact force with single isolated elements (blocks or tree trunks) during a debris flow event.

Currently, in Switzerland, the three components of impact pressure are calculated separately according to the VKF. The association suggests three equations to calculate the three different impact pressures exerted during the impact of a debris flow on building surfaces. The three proposed equations are presented in Table 9.

In the case of a granular debris flow, the static replacement pressure is already taken into account in the dynamic pressure equation with the pressure coefficient a = 4 [-]. In the case of a muddy debris flow, this pressure must be considered as an additional effect and thus calculated (the impact force is calculated according to the equations that apply for block and rockfall events).

5.1. Granular debris flow intensity proposition

The proposal for the hazard intensity assessment in this study is an adaptation of the VKF recommendations. As such, the intensity will be evaluated as a function of the velocity or height, plus the impact pressure of the debris flow. In order to determine the limits of the different intensity categories, the results of several studies in the field of debris flows as well as the historical study carried out in this work were taken into consideration.

The proposed intensity rating is as shown on Table 10.

In order to incorporate the debris flow impact pressure into the proposed intensity classification, it will be necessary to carry out an analysis based on the proposed debris flow velocities and heights in each intensity category. To this end, the impact pressure will be

Tab. 7 – Debris flow height values based on the theoretical and historical data.

Theoretical		
Height [m]	Source	Remark
0.5-3	VKF	According to the VKF the maximum height of the debris flow ranges between 0.5 and 3 [m]. As the debris flow spreads out, its height decreases.
Historical Survey		
Hauteur [m]	Event	Remark
9	Zouqu, Chine	Event classified as extreme.
6	Vargas, Venezuela	Event classified as extreme.
4	Brienz, Suisse	One of the largest debris flow events in Europe.

Tab. 8 – Velocity values based on the theoretical and historical data.

Theoretical		
Velocity [m/s]	Source	Remark
15-20	VKF	According to the AEAI, the velocity of a debris flow can reach 15 to 20 [m/s] only at places where a strong gradient is present. This velocity decreases to a value in the range of 2 to 7 [m/s] at locations where the gradient decreases
40-60	Erika Prina Howald	-
60	Philippe Coussot	-
Historical Survey		
Velocity [m/s]	Event	Remak
15	South Korea	Event classified as extreme.
10	Brienz, Switzerland	Maximum velocity occurrence registered in Europe.

Tab. 9 – Debris flow impact pressure components.

Pressure resulting from the dynamic solid stress q_f [kN/m^2]		Vertical surcharge due to materials deposited on a submerged building q_a [kN/m^2]		Static replacement pressure due to concentrated load (shock) q_e [kN/m^2]	
$q_f = a\rho_f v_f^2$	(4.1)	$q_a = g\rho_f h_a$	(4.2)	$q_e = \frac{Q_e}{A}$	(4.3)
q_f: pressure caused by the debris flow		q_a: surcharge due to debris flows		q_e: pressure caused by the debris flow	
a: pressure coefficient		g: gravitational acceleration		Q_e: impact force	
ρ_f: debris flow density		ρ_f: debris flow density		A: impact area	
v_f: flow velocity of the debris flow		h_a: flow height of the debris flow			

calculated according to equations (4.1) and (4.2).

As such, for a granular debris flow with ρ = 2.2 [t/m^3] and a = 4 [-], the results are presented in Tables 11 and 12.

Based on field investigations, as pointed out earlier in this work Zanchetta *et al*. (2014), were able to conclude that most buildings are completely destroyed as soon as the impact pressure exceeds 90 [kPa]. Following the results presented in Table 11 and Table 12, we can perceive that starting at a velocity of 3 [m/s] the dynamic pressure starts to grow much faster than the static pressure with heights in the same order of magnitude as the velocities. This is due to the fact that for granular debris flows, the pressure resulting from the impact force of singular elements is included in the equation for calculating the dynamic pressure. The latter implies that the pressure values obtained in Table 11 consider the two pressures: dynamic and static replacement.

This work's final proposal for the evaluation of the intensity of a granular debris flow, with the impact pressures added, is presented in Table 13.

Tab. 10 – Adaptation of VKF's debris flow intensity evaluation.

Intensity		Height of the debris flow h_f [m]		Velocity of the debris flow v_f [m/s]
1	Low	< 1	Or	< 1
2	Medium	$1 \leq h_f \leq 2.5$	Or	$1 \leq v_f \leq 3$
3	High	$2.5 < h_f \leq 5$	Or	$3 \leq v_f \leq 5$
4	Extreme	> 5	Or	>5

6. *Discussion*

In this paper, a brief historical study of past debris flow events in Europe and some of the most important around the world has been undertaken. This study was made in order to help determine the different types of building structures that have been exposed to debris flows in the past and to observe the different damages they have suffered. Based on this historical survey we have been able to define various types of building structure most vulnerable to this natural hazard.

Then, we have proposed a methodology for the assessment of building damage and debris flow intensity. The various proposals for damage assessment and hazard intensity assessment have emerged from thoughtful study. However, these are areas that require further, more profound research.

Regarding the different intensities, it may be interesting to do additional examinations in order to validate the response of the different structures. As for its quantification, there is still no equation that calculates the intensity of the hazard as a function of the total impact pressure of the debris flow. The total impact pressure considers several critical parameters: flow velocity and height, debris flow density, and impact force.

Tab. 11 – Impact pressure in fonction of the debris flow velocity.

Velocity of debris flow v_f [m/s]	0.5	1	2	2.5	3	3.5	4	5
Impact pressure q_f [KN/m^2]	2	9	35	55	79	108	141	220

Tab. 12 – Impact pressure in fonction of the debris flow height.

Height of debris flow h_f [m]	0.5	1	2	2.5	3	4	5	6
Impact pressure q_a [KN/m^2]	11	22	43	55	66	88	110	132

Tab. 13 – Evaluation of debris flow intensity used in this study.

Intensity		Debris flow height h_f [m]		Debris flow velocity v_f [m/s]	Impact pressure q_f [kPa]
1	Low	< 1	Or	< 1	< 22
2	Medium	$1 \le h_f \le 2.5$	Or	$1 \le v_f \le 2.5$	22-55
3	High	$2.5 < h_f \le 5$	Or	$2.5 < v_f \le 3.5$	56-110
4	Extreme	> 5	Or	> 3.5	> 110

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