Canadian Geotechnical Journal

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Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2020-0120.R2
Manuscript Type:	Article
Date Submitted by the Author:	25-Oct-2020
Complete List of Authors:	Luo, Hongyu; Hong Kong University of Science and Technology Zhang, L.M.; Hong Kong University of Science and Technology, Department of Civil Engineering He, Jian; Hong Kong University of Science and Technology Yin, Kesheng; Hong Kong University of Science and Technology, Dept of Civil and Environmental Engineering
Keyword:	Debris flow, building, physical vulnerability, fragility analysis, reliability analysis
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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Reliability based formulation of building vulnerability to debris flow impacts

H. Y. Luo^a, L. M. Zhang^{a *}, J. He^a and K. S. Yin^a

* Corresponding author

Email addresses: hluae@connect.ust.hk (H.Y. Luo), cezhangl@ust.hk (L. M. Zhang), jhebl@connect.ust.hk (J. He), kyinac@connect.ust.hk (K. S. Yin)

^a Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

Abstract: Physical building vulnerability to debris flows is defined as the potential damage degree of buildings for a given debris-flow intensity. In this paper, the physical characteristics on both debris flow intensity and building response are considered. Uncertainties in building capacity and debris flow intensity are explicitly quantified to evaluate the damage probability of a typical reinforced concrete building subject to debris flow impact. Four damage states with clear failure mechanisms are defined using multi-source information from field observations, numerical simulation and expert experience. Two series of fragility models have been proposed based on practical debris-flow impact pressure models. Several debris flow intensity measures are investigated. A better indication can be provided using the intensity measure that represents specific failure mechanism, for example, impact force ($h\nu^2$) for force-dominated failures or overturning moment ($h^2\nu^2$) for moment dominated failures, where h and ν are debris flow depth and velocity, respectively. The corresponding fragility surfaces best express the potential building damage. The intensity thresholds in the proposed fragility curves are consistent with those in empirical vulnerability curves. The methodology presented in this paper promotes the vulnerability assessment using physics based modeling, leading to a more reliable evaluation of building damage caused by debris flows.

Keywords: Debris flow, building, reliability analysis, physical vulnerability, fragility analysis.

1. Introduction

Debris flows pose threats to human lives, buildings and critical infrastructures in debris flow-prone mountain areas. Quantitative risk assessment has been utilized to provide an objective measure of the risk. As a critical component in risk analysis, vulnerability assessment has been studied from two diverse perspectives: social sciences and natural sciences (Fuchs et al. 2007). The natural science attribute, which is often related to the physical vulnerability, is the most frequently concerned in natural hazard risk analysis. Vulnerability is defined as the expected degree of loss for an element at risk as a result from the occurrence of a natural hazard of a given intensity, ranging from 0 (no damage) to 1 (total loss) (UNDRO 1979). Physical building vulnerability assessment establishes a relationship between debris flow intensity and building damage in a scientific manner.

In the literature, a vulnerability curve that relates building damage degree to debris flow intensity is often established by statistical regression (e.g., Fuchs et al. 2007; Quan et al. 2011; Jakob et al. 2012; Kang and Kim 2016; Peduto et al. 2017; Zhang et al. 2018, 2020). The building damage degree is often classified qualitatively without emphasizing the physical damage mechanism. A vulnerability factor (V) ranging from 0 (no damage) to 1 (complete damage) is assigned to a certain damage state. Therefore, the physical meaning of building damage is missing in the vulnerability curve.

Risk and the associated uncertainties are central features of geotechnical and geological engineering (Eidsvig et al. 2014; Bilgin et al. 2019; van der Krogt et al. 2019). Considering uncertainties in an explicit manner may significantly improve the quality of risk estimation efforts (Cassidy et al. 2008). In the vulnerability curve, the uncertainties can be quantified using a confidence band. However, only the range of the possible degree of loss is provided

without the exact probability distribution of each damage state for a given intensity (Eidsvåg et al. 2014). Sometimes, an event with a given intensity does not always cause the same amount of damage to a building when applying this model (Mavrouli et al. 2014). This is because the uncertainties related to both hazard intensity and building characteristics are not explicitly involved. A wide uncertainty bound is thus carried through the vulnerability assessment (McDougall 2017).

Inspired from seismic vulnerability assessment, the fragility curve, which expresses the probability of reaching or exceeding a certain damage state given a level of hazard intensity, is increasingly attractive for natural hazard assessment (Martinovic et al. 2017). The specific hazard characteristics, building failure mechanisms, and the associated uncertainties can be explicitly considered in such a fragility curve. It is obvious that the fragility curve carries more physical meaning than the vulnerability curve. However, limited literature on the fragility of buildings to debris flows can be found (e.g., Haugen and Kaynia 2008; Parisi and Sabella 2017; and Prieto et al. 2018). In the existing studies, the uncertainty in landslide intensity is often not studied. The building capacity is determined based on parameters for seismic effects; specific characteristics of building response to debris flow impact are not considered.

Although building vulnerability to debris flow has been examined extensively in the last decade, considerable research gaps still exist on (1) the quantification of the physical building damage; (2) the consideration of specific debris flow characteristics; and (3) the explicit evaluation of the associated uncertainties. The lack of the understanding on the interaction process and failure mechanisms of building structures caused by debris flows contributes to these gaps. Recently, Luo and Zhang (2018) and Luo et al. (2019, 2020) performed pioneering work on explicitly modelling the dynamic interaction between landslide debris and building structures. The building failure mechanisms discovered in the studies provide a

solid basis for formulating reliability-based vulnerability models for buildings subject to debris flow impact.

In this paper, fragility analysis is conducted based on interaction mechanisms between debris flows and a building. The physical building damage is clearly defined and quantified; the associated uncertainties on both debris flow intensity and building capacity are explicitly considered, promoting scientific knowledge on physical building vulnerability. In the following, the concept of reliability based fragility analysis is presented first. Then the debris flow intensity and the associated uncertainty are quantified. Subsequently, the identification of building damage state, building response mechanisms and the related uncertainties are presented. Finally a reliability based vulnerability model is formulated and validated.

2. Concept of reliability based fragility analysis

Reliability based analysis or fragility analysis is a scientific way to assess the conditional probability of reaching or exceeding a certain damage state of a building for a given intensity of debris flow impact. To conduct a reliability based fragility analysis, a performance function should be defined to represent the state of a building. In this study, the performance function $g(\mathbf{X})$ of a building structure under debris flow impact explicitly considers the load (L) induced by the impact of a given intensity and the building capacity (C) to the lateral impact:

$$(1) \quad g(\mathbf{X}) = C - L$$

$\mathbf{X}$ is the vector of basic variables involved in the performance function.

An appropriate probability distribution is assigned to every input variable, allowing for the explicit consideration of any uncertainties in both the load and the capacity. The probability distributions for these two components thus can be obtained in terms of the engineering demand parameter (EDP) which represents physical response of the building

(Fig. 1(a)). The exceedance probability, P , can be calculated by:

$$(2) \quad P = P[g(\mathbf{X}) < 0]$$

In this paper, Monte Carlo simulation is used to solve Eq. (2). By randomly generating N samples based on prescribed probability distributions, the exceedance probability can be evaluated by:

$$(3) \quad P = \int_{D_t=\{\mathbf{X}:g(\mathbf{X})<0\}} f_{\mathbf{X}}(\mathbf{X}) d\mathbf{X} = \int I[g(\mathbf{X}) < 0] f_{\mathbf{X}}(\mathbf{X}) d\mathbf{X} \approx \frac{1}{N} \sum_{i=1}^N I[g(\mathbf{X}_i) < 0]$$

where $f_{\mathbf{X}}(\mathbf{X})$ is the joint probability distribution function; N is times of Monte Carlo simulation; $\mathbf{X}_i$ is the i th generated sample based on the probability distribution function of $\mathbf{X}$; and $I[g(\mathbf{X}) < 0]$ is an indicator function defined as:

$$(4) \quad I[g(\mathbf{X}) < 0] = \begin{cases} 1 & g(\mathbf{X}) < 0 \\ 0 & g(\mathbf{X}) \geq 0 \end{cases}$$

The output of the fragility analysis is a set of fragility curves which present the relationship between the debris flow intensity and the exceedance probability of the building for a certain damage state, i.e., slight, moderate, heavy and complete damage state (Fig. 1(b)). For any given hazard intensities, discrete damage state probabilities are calculated as the difference of the probability of reaching or exceeding successive damage state, which can be further used for loss estimation. Fig. 2 shows the procedure for the development of fragility curves for a building subjected to debris flow impacts, including quantification of debris flow intensity, identification and quantification of building damage states, inclusion of uncertainties and derivation of the fragility curves.

A prerequisite for establishing a physics-based fragility model is to understand debris flow-building interaction mechanisms. The dominant failure modes should be extracted to formulate the complex problem scientifically. Based on the identified mechanisms, governing variables are selected to quantify debris flow intensity and the physical building damage. For

a certain damage state, either an analytical or numerical model is chosen to obtain the building response to a given debris flow. Then, by explicitly considering the uncertainties in the governing variables, the probability of reaching or exceeding each damage state can be calculated using advanced reliability analysis approaches. The reliability based vulnerability models thus can be formulated in a scientific manner.

3. Debris-flow impact load and associated uncertainties

The debris flow intensity is quantified by impact load. In the literature, a number of studies have been carried out to investigate debris flow-structure interaction mechanisms and the impact load (e.g., Hungr et al. 1984; Zhang and Yuan 1985; Hübl and Holziger 2003; Tiberghien et al. 2007; Proske et al. 2011; Scheidl et al. 2013; Cui et al. 2015; Ashwood and Hungr 2016; Ng et al. 2016; Song et al. 2017). A hydro-dynamic model with a uniform pressure distribution (Fig. 3(a)), which is most commonly used to estimate the impact pressure, is expressed as:

$$(5) \quad p_h = \alpha \rho v^2$$

where p_h is the debris impact pressure; α is a dynamic empirical factor; ρ is the density of debris; and v is the frontal flow velocity. Design guidelines published in China, Japan, and Canada recommend the use of this model (Kwan 2012).

A special representation of the hydro-dynamic formula (i.e. the power model), which is adopted in Austria (ASI 2008), is given by Hübl and Holziger (2003) as:

$$(6) \quad p_p = m Fr^n \rho v^2$$

where m and n are two coefficients; Fr is the Froude number that is defined as $v/(gh)^{0.5}$; h is the debris flow depth. A trapezoid pressure distribution is used in this model (Fig. 3(b), Proske et al. 2011).

The hydrodynamic model adopts an empirical factor α to consider various uncertainties,

including particle size, solid concentration and impact mechanism. This value has been deduced by many researchers through experiments and field observations (Zhang and Yuan 1985; Hubl and Holziger 2003; Tiberghien et al. 2007; Proske et al. 2011, Scheidl et al. 2013; Cui et al. 2015). The empirical coefficient was estimated at 0.12–18.6. The relationship between Fr and α can be established by data fitting (Fig. 4).

As both impact pressure estimation models have been adopted in practice guidelines, fragility analysis has been carried out based on each model and hence two sets of fragility curves are presented. The uncertainty on the debris flow intensity is considered by taking the empirical factors in the impact pressure estimation models as random variables. Based on 130 sets of data in the literature (Fig. 4), statistical analysis is conducted to obtain the probability distributions for α in the hydrodynamic model and m in the power model. The n value in the power model is regarded as a constant that defines the trend line (Fig. 4).

The probability density distributions and cumulative probability distributions for α and m are shown in Fig. 5. The normal, lognormal, generalized extreme value, Gamma and Weibull functions were used for fitting. The goodness-of-fit of each probabilistic model was assessed using the K-S test. The test statistics for the lognormal distribution are 0.085 and 0.0421 for α and m samples, respectively. Both are smaller than the critical value of 0.1178, indicating that the lognormal distribution well describes the probability distributions of the two variables and hence are further applied in the Monte Carlo simulation to quantify the uncertainty on debris flow intensity.

It is worth noting that the above two models are applicable to fine debris flows. Predominant impulse loads can be induced by bouldery debris flows, in which large boulders or rock fragments are involved in the flow mass. Although the α or m value in the adopted model implicitly covers some of the impact loads by large boulders or rock fragments (Song et al. 2019), the sharp impulse loads cannot be well described. Such loads can cause severe

damage to structures and the failure mode of buildings may change, e.g., from global pushover failure to progressive failure of local columns. The load estimation models adopted here may underestimate the impact loads from bouldery debris flows.

4. Building capacities and associated uncertainties

Before going into the detailed analysis of the building response upon a debris flow impact, the building damage states are identified first. The interaction between debris flow and building is a complex dynamic process. It is challenging to accurately predict the building response under a debris flow impact of certain intensity, as building damage depends not only on the flow intensity but also building characteristics. Different building structural types have different resistances to lateral impacts. In this study, fragility analysis is conducted on a reinforced concrete frame structure, which is a common building structural type.

In the literature, classification systems for degree of damage of reinforced concrete buildings induced by debris flow impact have been proposed by Hu et al. (2012), Mavrouli et al. (2014) and Kang and Kim (2016). Generally, four types of damage states as those adopted in the classification system for seismic damage to building are defined, i.e. slight, moderate, heavy and complete damage state. However, as these classification systems are established based on expert experience, the description of the damage levels is qualitative and not unified (Table 1). To better classify the building damage state due to debris flow impacts, field observations and findings from numerical simulation are utilized to provide insight into the damage development and failure mechanisms of buildings. Combining the multi-source information about building damage, the building damage states identified here, from slight damage to complete collapse, are out-of-plane failure of frontal walls, in-plane cracking shear failure of side walls, bending failure of columns and pushover failure of the building frame. The former three damage states can be regarded as localized structural element failures which

occur progressively. The pushover failure is a global failure of the building frame. A reliability based vulnerability model can be solidly established based on the identified failure mechanisms for each damage state.

Combining the identified building damage states with the impact pressure estimation models, the load and building capacity for each damage state can be obtained through static analysis or numerical simulation. Fig. 6 presents diagrams of the failure mechanism for each damage state. The building capacity for the complete damage state which represents the global failure of building frame is captured using finite element analyses. Static analyses are performed to identify the thresholds for the heavy, moderate and slight damage states which describe the local failure of building components, e.g., columns and walls. The specific analysis methods will be detailed in the following sections.

4.1 Complete damage state

The complete damage state describes the global failure of building frame (Fig. 6(a)). As stated in FEMA (2017) in which the building damage induced by tsunami impact is evaluated, damage to a structural system is governed solely by tsunami flow impact characterized by the total lateral force on the structure. Global failure will occur when the impact force (L) exceeds the ultimate lateral force capacity (C) of the building frame. To identify the building capacity to the lateral impact, static nonlinear (pushover) analysis in which the gravity loaded building frame is subjected to a monotonically increasing lateral load is conducted considering specific debris flow characteristics (e.g., Fig. 3). For each pushover analysis, the lateral load will increase till the ultimate state of building is reached and a pushover curve which describes the relationship between the load and the lateral displacement at the roof can be obtained. Following the method in FEMA (2017), the maximum lateral force obtained from the pushover curve is adopted to represent the lateral

capacity of the building frame (F_{c-f}). The total impact force on the building frame is regarded as the load (F_{l-f}), which is calculated based on Eqs. (5) and (6).

It is worth noting that typical pushover analysis focuses on the global failure of the building frame; failure of individual structural elements, for example, the out-of-plane failure of wall, in-plane failure of wall and column failure cannot be captured (FEMA 2017). In this study, this limitation has been remedied by separately analyzing the failure of local components using static analyses.

The pushover analysis is performed on a 2-bay (4.8 m), 3-span (3.6 m) and 3-story (3.6 m) RC framed structure. It is assumed that the building has its longer dimension facing the flow. A three-dimensional (3D) model of the reinforced concrete building frame is developed in *OpenSees*. Both columns and beams are modeled using distributed plasticity force-based elements with nonlinear fiber sections (Scott and Fenves 2006). Each fiber section is composed of several fibers, with each fiber containing a uniaxial material (Fig. 6(a)). The uniaxial stress-strain behaviors of the core and cover concrete are modeled using Concrete01 (Scott et al. 1982), which considers strain-softening behavior, confinement effect and has no tensile capacity. A bilinear stress-strain relationship (Steel01) with a strain-hardening ratio of 0.01 is adopted for the reinforcements.

The loading height applied on the building has significant effects on the building response, as mentioned by Attary et al. (2017). Therefore 12 flow depths (from 0.6 m to a two-storey height of 7.2 m with an interval of 0.6 m) for the two predefined loading distributions are considered. 5,000 analysis cases are generated for each depth considering the uncertainties arising from the building material properties. The basic random variables for describing the building characteristic are listed in Table 2. The probability distribution for the building lateral capacity under a given debris flow depth thus can be obtained. The debris flow density is considered to follow a lognormal distribution with a mean value of 1800

kg/m³ and a COV of 0.2 (Suda et al. 2009; Proske et al. 2011; Parisi and Sabella 2017; Prieto et al. 2018). The lognormal distribution is also assigned to the building material properties; the mean values and coefficients of variation are set based on MOHURD (2010, 2011), Mirza and MacGregor (1979), Attary et al. (2017) and Parisi and Sabella (2017).

Figure 7 gives two examples of the fitted probability distribution for the building lateral capacity under flow depths of 3 m and 6 m using the hydrodynamic model. The generalized extreme value (GEV) distribution is adopted following Parisi and Sabella (2017), who tested common probability distribution functions for building capacity. EN 1990 also recommends the extreme value distribution for uncertainty modelling of building structures. The building frame in this study has a higher mean lateral capacity of 660.6 kN under the 3 m debris flow depth than that of 564.3 kN under the 6 m debris flow depth, which is consistent with the previous statement that the height of the distributed load on the building can affect the building response.

4.2. Heavy damage state

The heavy damage state describes the bending failure of reinforced columns (Fig. 6(b)). The column on the ground floor is usually fixed at the bottom, with free horizontal movements and restrained rotation at the top (Zeng et al. 2015). The bending moments in the column, based on the hydrodynamic model and power model, can be calculated as:

$$(7) \quad M_{h-l-c} = \frac{p_h h^2}{2} - \frac{p_h h^3}{6h_c}$$

$$(8) \quad M_{p-l-c} = \frac{p_p h^2}{4} - \frac{7p_p h^3}{96h_c}$$

where p_h and p_p are the impact pressure induced by the debris flow and are calculated using Eqs. (5) and (6), respectively; and h_c is the column height ($h \leq h_c$). When the debris flow depth exceeds the height of column, the impact depth h is equal to the column height.

The bending capacity of a column can be calculated based on force equilibrium (Eq. (9)) and moment equilibrium (Eq. (10)):

$$(9) \quad f_y A_s = \alpha_1 f_{ck} b x + f_y' A_s'$$

$$(10) \quad M_{c-c} = \alpha_1 f_{ck} b x \times (h_0 - \frac{x}{2}) + f_y' A_s' (h_0 - a_s')$$

where f_y and f_y' are the tensile and compressive strengths of the longitudinal reinforcement, respectively; A_s and A_s' are the areas of tensile and compressive longitudinal reinforcement, respectively; α_1 is a coefficient of concrete grade; f_{ck} is the concrete compressive characteristic strength; b is the width of column section; x is the compression height; and h_0 is the effective height of the cross section. If $x < a_s'$, the compressive stress of the rebar does not reach f_y' , so the ultimate bending moment can be calculated by assuming $x = a_s'$ and taking a moment to the centroid of the compressive rebar, $M_{c-c} = f_y A_s (h_0 - a_s')$.

4.3. Moderate damage state

The moderate damage state describes the in-plane cracking shear failure of side walls (Fig. 6(c)). The load on the side wall under in-plane lateral loading is equal to the total impact force transferred from the columns (F_{l-sw}). The diagonal crack failure loading of the side wall is calculated using the method proposed by Saneinejad and Hobbs (1995), which has been applied in FEMA 306. The method is developed based on the data generated from experimental studies as well as results from a series of nonlinear finite-element (NLFE) analyses. The capacity of side walls for the in plane cracking failure is expressed as:

$$(11) \quad F_{c-sw} = \frac{2\sqrt{2} L_{inf} t_{inf} \sigma_{cr}}{(\frac{L_{inf}}{h_{inf}} + \frac{h_{inf}}{L_{inf}})}$$

where L_{inf} is the side wall length, mm; t_{inf} is the side wall thickness, mm; h_{inf} is the side wall height ($(h \leq h_{inf})$), mm; and σ_{cr} is the cracking strength of the masonry material.

4.4. Slight damage state

The slight damage state describes the out-of-plane flexural failure of frontal brick walls (Fig. 6(d)). According to the specification for the design of infill walls in reinforced concrete buildings (MOHURD 2011), the top and bottom ends of the external wall are assumed as fixed ends. Under such a condition, bending failure of the frontal brick walls is a dominant failure mechanism when subject to lateral loading (Lei et al. 2016). The bending moments on the frontal wall calculated based on the hydrodynamic model and the power model are respectively expressed as:

$$(12) \quad M_{h-l-fw} = \frac{p_h h^2 \times (6h_f^2 - 8hh_f + 3h^2)}{12h_f^2}$$

$$(13) \quad M_{p-l-fw} = \frac{p_p h^2 \times (30h_f^2 - 35hh_f + 12h^2)}{120h_f^2}$$

The bending capacity of the frontal wall is expressed as:

$$(14) \quad M_{c-fw} = f_m W$$

where h_f is the height of frontal wall ($h \leq h_f$); f_m is the flexural tensile strength of the masonry material; and W is the resistance moment of the section.

5. Reliability based vulnerability models

5.1. Single intensity measures

Certain debris flow intensity measures are required in a vulnerability model. The selection of intensity measures which describe hazard characteristics is critical for generating fragility models. It is found that the flow depth (h) is commonly used to express the debris flow intensity, as it can be obtained easily in the field. However, for a given flow depth, the debris flow intensity still cannot be clearly represented due to the variation of flow velocity.

With the aid of advanced numerical modeling, other intensity measures such as flow velocity (v), hydrodynamic impact pressure (ρv^2), impact force measure ($h v^2$) and overturning moment measure ($h^2 v^2$) have been used to quantify the debris flow intensity (Quan et al. 2011; Jakob et al. 2012; Zhang et al. 2018). Different intensity measures represent specific physical characteristics. The abilities of these measures to describe the debris flow intensity are not examined yet. In this study, efforts are made to evaluate effective intensity measures.

Figures 8(a) and 8(b) show the calculated exceedance probability for the complete damage state with respect to flow depth and flow velocity, respectively, using the hydrodynamic model. The trend line indicates the average probability for each damage state, which is obtained by calculating the average value of P within a certain interval of intensity. There is a large variation of the exceedance probability under a given flow depth or a given flow velocity. Such variation also occurs in the existing empirical vulnerability curves, in which a single intensity measure, e.g., flow depth, is adopted (e.g., Zhang et al. 2018; Kang and Kim 2016; Fuchs et al. 2007). In fact, both flow depth and flow velocity are important characteristics for debris flow intensity. A single intensity measure cannot provide full information of the hazard characteristics, leading to the inaccurate estimation of the potential building damage. Note that the hydrodynamic impact pressure is a measure similar to the flow velocity.

Figure 9 presents the calculated exceedance probability for each damage state based on the impact force measure ($h v^2$) using the hydrodynamic model. Jakob et al. (2012) and Zhang et al. (2018) have utilized the impact force as an intensity measure. It is obvious that the data points concentrate on a clear trend line. The correlation between the exceedance probability and hazard intensity is much better than that in Fig. 8. Specifically, the correlations for the moderate and complete damage states are better than those for the slight and heavy damage states. This is because the failure mechanism in the moderate and complete damage states is

governed by the impact force. An exceedance probability of 0.8 for the complete damage state is obtained when a threshold value of $hv^2 = 360 \text{ m}^3/\text{s}^2$ is reached.

The same set of figures for the power model is shown in Fig. 10. Good correlation is also found in the moderate and complete damage states. The exceedance probability of 0.8 for the complete damage is determined when a threshold value of $Fr^{-1.5}hv^2 = 100 \text{ m}^3/\text{s}^2$ is reached. Note that the impact force measure for the power model is calculated as $Fr^{-1.5}hv^2$. Without considering Fr in the calculation of intensity measure, the theoretical basis of the power model will be missed, leading to a large scatter of the probability data points.

Figures 11 and 12 give the calculated exceedance probability for each damage state based on the overturning moment measure (h^2v^2) using the hydrodynamic model and the power model, respectively. This moment measure has been adopted by Quan et al. (2011) and Zhang et al. (2018). It is observed that the correlations developed based on the overturning moment, as expected, are more appropriate for the slight and heavy damage states, in which the failure mechanism is governed by the bending moment. The exceedance probability of 0.8 for the complete damage state is determined when a threshold h^2v^2 value of $1800 \text{ m}^4/\text{s}^2$ or an $Fr^{-1.5}h^2v^2$ value of $450 \text{ m}^4/\text{s}^2$ is reached.

5.2. Multi-intensity measures

Although the composite intensity measures, hv^2 and h^2v^2 , have been used in the two impact pressure estimation models, comparison of the fragility curves between the two models is still not convenient. To overcome this shortcoming, the flow depth and flow velocity are regarded as two independent intensity measures as suggested by Attary et al. (2017) for tsunami impacts. The fragility surfaces for each damage state using the hydrodynamic model and the power model are shown in Figs. 13 and 14, respectively. Also, the corresponding fragility contours, which are more convenient to use in practice are given

in Figs. 15 and 16. These fragility models are developed as functions of both flow depth and flow velocity, resulting in an accurate expression of debris flow intensity.

For the fragility surfaces developed using the power model, the flow depth has a more dominant influence on the building damage than the flow velocity. For example, the heavy and complete damage state may not occur if the flow depth is less than 1 m when using the hydrodynamic model; whereas a limiting flow depth of 1.8 m is observed for the power model. Moreover, based on the power model, if the flow depth increases to 3.6 m, which is the storey height, the probability of reaching or exceeding the heavy damage state is over 0.6; the probability of reaching or exceeding the complete damage state is over 0.8 if a flow depth of 5 m is reached, regardless of the flow velocity. Special attention thus should be paid on the estimation of the flow depth when applying the power model to quantify the debris flow intensity.

In order to quickly estimate the potential damage state of a building to a given debris flow impact, contours of an exceedance probability of 0.5 for each damage state are combined in Fig. 17. The hierarchy of the contours is clear for the two debris flow impact pressure estimation models, implying that the predefined damage states are appropriate and reflect well the damage development under debris flow impacts. Smith et al. (2012) also proposed similar failure threshold contours for wooden buildings impacted by floods. It is worth mentioning that due to the static analysis setting, the flow depth cannot exceed the storey height for the proposed contours of the slight, moderate and heavy damage states. When the flow depth exceeds the storey height, the local components will have a high failure probability according to field observations (Zeng et al. 2015).

5.3. Comparison of the proposed vulnerability models

The proposed vulnerability models are validated by comparing the proposed models

with the existing models in the literature. The brick concrete (BC-) buildings (also called unreinforced masonry buildings) are the most studied in the literature whereas only a few vulnerability models are available for reinforced concrete (RC-) buildings (e.g., Zhang et al. 2018; Prieto et al. 2018). To make better use of the limited field data, two assumptions are adopted here. First, as the moderate damage state here represents severe damage on brick walls, the threshold of the debris flow intensity to reach a vulnerability factor of 1.0 in the existing BC-building vulnerability curves corresponds to an exceedance probability of 0.8 for the moderate damage state in the fragility curves. Second, the threshold of the debris flow intensity to reach a vulnerability factor of 1.0 in the existing RC-building vulnerability curves corresponds to an exceedance probability of 0.8 for the complete damage state in the fragility curves. The 80% exceedance probability is adopted based on Haugen and Kaynia (2008). The debris flow intensity thresholds in the proposed models are compared with those in the existing models, in terms of the impact force measure (hv^2) and the square root of overturning moment measure (hv).

The intensity thresholds to reach the complete damage state for brick concrete buildings are compared in Table. 3. Both the hv^2 threshold and the hv threshold in this study are similar to the values proposed by Zhang et al. (2018). Jakob et al. (2012) gave a range for the impact force thresholds. A smaller threshold of hv for reaching the vulnerability factor 1.0 is suggested by Quan et al. (2011). Prieto et al. (2018) provides a significant lower value of the impact force threshold than the result in this study.

Table 4 compares of the thresholds to reach the complete damage state for reinforced concrete buildings. It is found that the hv^2 threshold and the hv threshold in this study are also close to the values proposed by Zhang et al. (2018), in which the vulnerability curves are developed using a comprehensive building damage database. The fragility curves proposed by Prieto et al. (2018) still provide a significant lower impact force threshold than the result

in this study. Besides, it is worth mentioning that Haugen and Kaynia (2008) utilized the lateral displacement, as in seismic design code, to quantify the building capacity to debris flow impact. An unrealistically large lateral displacement value is required for a two-storey building to reach 80% or higher probability of complete damage.

The building fragility curves in Haugen and Kaynia (2008) and Prieto et al. (2018) are developed by directly adopting seismic design parameters. These seismic design parameters are obtained from the pushover analysis that applies an inverse triangularly distributed lateral load considering earthquake characteristics. It is obvious that the loading height along the building affects the building capacity. For example, increasing the height of the distributed load on a building will decrease the equivalent stiffness of the building, leading to a lower lateral capacity and a larger lateral displacement. Therefore, directly applying the seismic design parameters to calculate the lateral capacity will underestimate the building capacity to debris flow impact; on the contrary, adopting the lateral displacement in seismic design code will overestimate the building capacity to debris flow impacts. The discrepancies on the existing fragility models thus can be explained.

In summary, the reliability based building vulnerability models are formulated in three formats: fragility curves, fragility contours, and fragility surfaces. The comparison of proposed fragility models with the existing empirical vulnerability models shows good consistency. The vulnerability models in this study carry physical meanings and provide an attractive alternative for evaluating the building damage caused by debris flows.

5.4. Application of the proposed vulnerability models

According to ISO 31000:2018, risk is the effect of uncertainty on objectives. ISSMGE (2004) defines risk as the measure of the probability and severity of an adverse effect to life, health, property, or the environment. Standard procedure of geotechnical risk analysis

generally includes definition of scope, identification of threats, estimation of probability of occurrence, evaluation of the vulnerability of the elements at risk, consequence identification, and risk estimation. Vulnerability evaluation plays a critical role as it links the hazard estimation and identification of elements at risk. The quantification of uncertainties should be addressed, not only in the vulnerability evaluation but also in the entire analysis procedure, to better perform quantitative risk analysis.

The fragility models in this study are developed based on specific debris flow characteristics. The physical building damage is clearly quantified and the uncertainties associated with both the debris flow intensity and the building capacity are explicitly addressed. The building vulnerability thus can be assessed in a probabilistic way, achieving a more reliable prediction of building damage induced by debris flows. The proposed vulnerability models can be applied either to a single building or to a group of buildings (Eidsvig et al. 2014). House owners can quickly estimate the exact probability of a certain damage state for a single building, supporting local structural protection; the distribution of damage to a group of buildings can also be obtained for the authority to effectively allocate defensive resources.

6. Summary and conclusions

Reliability based analysis has been conducted to evaluate the building damage probability to debris flow impacts considering specific hazard characteristics and building damage mechanisms. Four damage states of reinforced concrete buildings, namely, slight, moderate, heavy and complete damage states, are defined by combining the information from expert experience, field observations and failure mechanisms from numerical simulations. Two sets of reliability-based vulnerability models are proposed based on two debris flow impact pressure estimation models adopted in practice. Several key conclusions are drawn:

1. Flow depth (h) or flow velocity (v) alone does not sufficiently indicate the building damage state as the debris flow intensity is related to both flow depth and flow velocity. Composite factors, e.g., impact force (hv^2) and overturning moment (h^2v^2) are more suitable measures of debris flow intensity. The intensity measure should be chosen based on specific failure mechanism, i.e., force dominated or moment dominated mechanism.
2. The fragility surfaces best express potential building damage. In these proposed models, the flow depth and flow velocity are treated as two independent intensity measures to fully represent the debris flow intensity.
3. The fragility models calculated based on the hydrodynamic model are gentler than these developed using the power model. In the power model, the flow depth has a more dominant influence on the building damage than the flow velocity, and the damage probability will increase dramatically with the flow depth. Cautions should be exercised when applying the power model to quantify the debris flow intensity.
4. Comparison of proposed fragility models with the existing empirical vulnerability models shows that the intensity thresholds in fragility curves are consistent with the values in the existing vulnerability curves. The specific debris flow-building interaction characteristics can lead to distinct differences in the threshold intensity values.

Acknowledgements

The authors acknowledge the support from the Research Grants Council of the Hong Kong SAR (Nos. T22-603/15N and C6012-15G).

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Table. 1 Definition of building damage states

Damage states	Field evidences	Numerical observations (Luo et al. 2019)	Qualitative descriptions
Slight			<ul style="list-style-type: none">● Columns and beams are intact, only some walls are partially damaged (Hu et al. 2012); Breakthrough of large or weak opening (Mavrouli et al. 2014); Slight non-structural damage, stability not affected, damage to furnishings or fittings (Kang and Kim 2016)● Frontal wall – out-of-plane flexural failure
Moderate			<ul style="list-style-type: none">● A minority of columns and beams are damaged, some walls are broken (Hu et al. 2012); Moderate damage to the infill panels in RC buildings (Mavrouli et al. 2014); Cracks in the wall, stability unaffected, flooding of the internal rooms (Kang and Kim 2016)● Side wall – in-plane cracking shear failure
Heavy			<ul style="list-style-type: none">● A majority of columns and beams are broken, most walls are broken, part of the roof falls in (Hu et al. 2012); Severe damage to structural elements (Mavrouli et al. 2014); Partly destroyed, loss of parts of external and internal walls, evacuation necessary (Kang and Kim 2016)● Column - bending failure
Complete	<small>Photocredit: Tang et al. (2011)</small>		<ul style="list-style-type: none">● Less than 50% of the building's framework survives (Hu et al. 2012); Partial or total collapse of structural elements (Mavrouli et al. 2014); Partly or totally destroyed, evacuation necessary, complete reconstruction (Kang and Kim 2016)● Building frame - pushover failure

Table 2 Basic variables

Category	Variable	Mean	SD	Distribution
Debris flow intensity	Bulk density, ρ (kg/m ³)	1800	360	Lognormal
	α value in hydrodynamic model	2.73	3.3	Lognormal
	m value in power model	6.45	2.72	Lognormal
Frontal wall	Tensile strength, f_m (MPa)	0.53	0.08	Lognormal
Side wall	Compressive strength, f'_m (MPa)	3.02	0.453	Lognormal
Reinforced component (column/frame)	Compressive strength, f_{ck} (MPa)	20.1	3	Lognormal
	Elastic modulus, E (GPa)	200	20	Lognormal
	Yield strength of rebar, f_y (MPa)	400	40	Lognormal

Table 3 Comparison of the threshold values to reach the complete damage state for brick concrete building

Parameters	Sources	Impact force measure, hv^2 (m ³ /s ²)	Square root of overturning moment measure, hv (m ² /s)
Threshold of vulnerability factor for the complete damage degree ($V = 1$)	Quan et al. (2011)	-	14.6
	Jakob et al. (2012)	100-1000	-
	Zhang et al. (2018)	132	20.1
Threshold of exceedance probability for the complete damage state ($P = 0.8$)	Prieto et al. (2018)	84 (USA pre-code) 50 (Colombia)	-
Threshold of exceedance probability for the moderate damage state* ($P = 0.8$)	This study	145	20.4

*Note: As the moderate damage state in this study represents severe damage on brick wall, the complete damage state for brick concrete building thus refers to the moderate damage state in this study.

Table 4 Comparison of the threshold values to reach the complete damage state for reinforced concrete building

Parameters	Sources	Impact force measure, hv^2 (m ³ /s ²)	Square root of overturning moment measure, hv (m ² /s)
Threshold of vulnerability factor for complete damage degree ($V = 1$)	Zhang et al. (2018)	364	55.7
Threshold of exceedance probability for the complete damage state ($P = 0.8$)	Prieto et al. (2018)	79	-
Threshold of exceedance probability for the moderate damage state ($P = 0.8$)	This study	400	42

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