Nat Hazards (2012) 64:2107–2128
DOI 10.1007/s11069-012-0124-6

ORIGINAL PAPER

Building vulnerability to debris flows in Taiwan: a preliminary study

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Received: 20 August 2011 / Accepted: 19 February 2012 / Published online: 27 March 2012

Abstract In quantitative risk analyses for natural hazards, vulnerability can be expressed as the ratio of reconstruction, replacement or reproduction expenses due to a damage caused by a certain process intensity and the original value of the element at risk exposed. To discuss the building vulnerability under debris flow events, the ratio is mostly related to debris flow inundation height, building materials and building values. Different types of buildings would resist to the impact of debris flows differently, resulting in different damage levels even under the same inundation height. After debris flow events, the damages to a building include the content loss and the structure loss, which is also variable due to the individual building conditions. This study proposes a flowchart to establish building vulnerability curves through estimating the damages to buildings after debris flow hazards. The losses of content and structure are firstly calculated separately to obtain the loss ratios with respect to original buildings. Secondly, by combining the content and structure loss ratio, the building vulnerability function is derived. In this paper, the original building content value was obtained from governmental statistic records and was based on the market price, and the structure value was received from a regional architecture office. The losses resulting from debris flow impacts were synthetically derived following field surveys. To combine the content and structure losses, a unit building with a floor area of 60 m^2 was assumed. The result shows that due to a higher percentage of content value compared with the total building value, the loss ratio resulting from debris flows in Taiwan is higher compared with European studies, in particular with respect to high-frequency but low-magnitude events. The concept of obtaining building vulnerability is particularly suitable for regions where well-documented building loss records are unavailable.

Keywords Vulnerability · Debris flow · Risk analysis · Building content · Building structure · Taiwan

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1 Introduction

Natural hazard is defined as a natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR 2009). As for natural disaster risk, risk can be defined as the likelihood or, more formally, the probability that a particular level of loss will be sustained by a given series of elements as a result of a given level of hazard. The elements at risk consist of the population, communities, the built environment, the natural environment, economic activities and services which are under threat of disasters in a given area (Alexander 2000).

UNDRO (1979) defined risk by Eq. 1 as:

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \tag{1}$$

Risk:	Risk is measured as expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular natural phenomenon and is consequently materialized in natural sciences as the product of hazard times elements at risk times vulnerability
Hazard:	Hazard is the probability of occurrence of a potentially damaging natural phenomenon within a specific period of time in a given area
Exposure:	Exposure describes the proneness of elements at risk such as the population, buildings and civil engineering works, economic activities, public services, utilities and infrastructure toward a hazard
Vulnerability:	Vulnerability is materialized in natural sciences as the degree of loss of a given element at risk or set of such elements resulting from the occurrence of a natural phenomenon of a given magnitude and is expressed on a scale from 0 (no damage) to 1 (total loss)

This definition had been applied for natural hazard risk analyses in various fields, in particular with respect to mountain hazards (e.g., Varnes 1984; Glade 2003; Bell and Glade 2004; Hufschmidt et al. 2005; Papathoma-Köhle et al. 2007; Peduzzi et al. 2009; Huttenlau and Stötter 2011).

In Taiwan, a similar procedure for quantitative risk analyses was proposed in 2008 (Fig. 1; Tsao et al. 2010), focusing on debris flow hazards. This procedure includes three components:

1. Scope definition: To identify the area of interest and the types of losses to be analyzed.
2. Risk identification: To identify and collect data of elements at risk and debris flow occurrence through field investigation.
3. Risk estimation: To analyze the hazard and the related consequences. Debris flow simulations with different return periods have to be conducted for hazard analysis in order to assess magnitude and frequency, and the affected elements at risk and their vulnerability toward debris flows have to be quantified.

The proposed procedure is based on a GIS environment which is targeted at a spatially explicit quantification of risk (Fig. 2). Therefore, information on vulnerability is needed.

Following this concept, Dai et al. (2002), Bell and Glade (2004), Fuchs et al. (2007), and Friele et al. (2008) had further diversified Eq. 1 for landslide or debris flow risk analysis. Following the same concept, Tsao et al. (2010) proposed Eq. 2 for quantitative debris flow risk analyses in Taiwan.

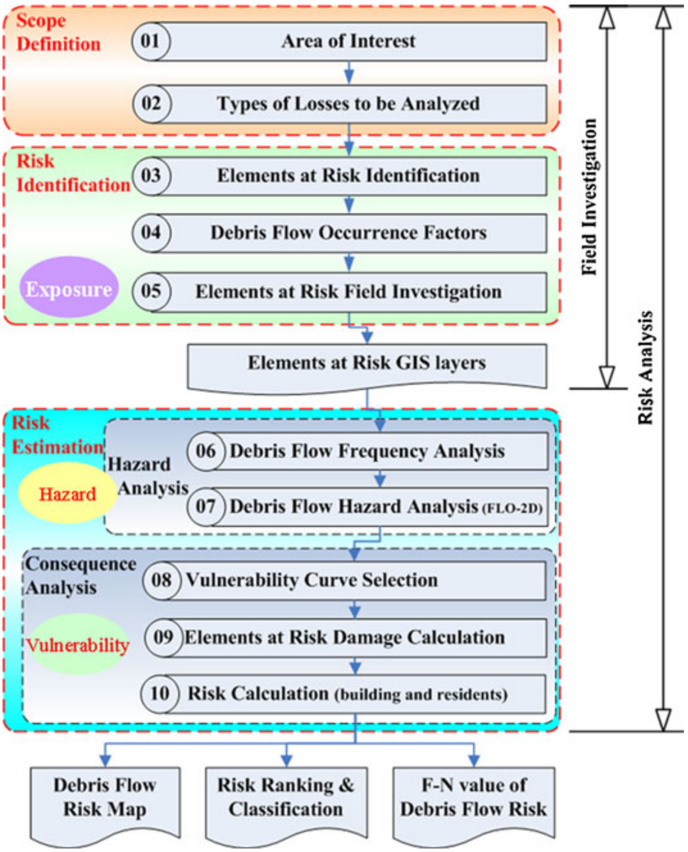


Fig. 1 Debris flow risk analysis procedure (modified after Tsao et al. 2010)

$$L_{\text{prop}|H} = \sum_{j} P_{S|H,j} \times P_{T|S,j} \times V_{\text{prop}|S,j} \times E_{\text{prop},j} \qquad (2)$$

where $L_{\text{prop}|H}$ = the summation of all damages to each element at risk, under a certain debris flow hazard event; j = the total number of the elements; $P_{S|H,j}$ = the probability of the spatial impact of a debris flow event on each element at risk exposed; $P_{T|S,j}$ = the probability of temporal impact on each element at risk; $V_{\text{prop}|S,j}$ = the vulnerability of each type of element at risk; $E_{\text{prop},j}$ = the economic value of each element at risk. When discussing debris flow risk analyses for buildings exposed, the variable $V_{\text{prop}|S}$ becomes a vital component and represents the vulnerability of buildings exposed to a debris flow impact.

However, depending on the field of science, the definition of the term ‘vulnerability’ shows a high variability. Thywissen (2006) listed at least 36 different definitions that were used in various previous studies. The notion of vulnerability applied in this study and discussed in Eq. 2 is similar to physical vulnerability (Roberts et al. 2009; Papathoma-Köhle et al. 2011) or structural vulnerability (Fuchs 2009) used in previous studies. However, other definitions of vulnerability frame the natural-scientific approach, are therefore of considerable importance for an overall vulnerability framework, and are listed below ranging from large-scale conceptualizations to small-scale applications.

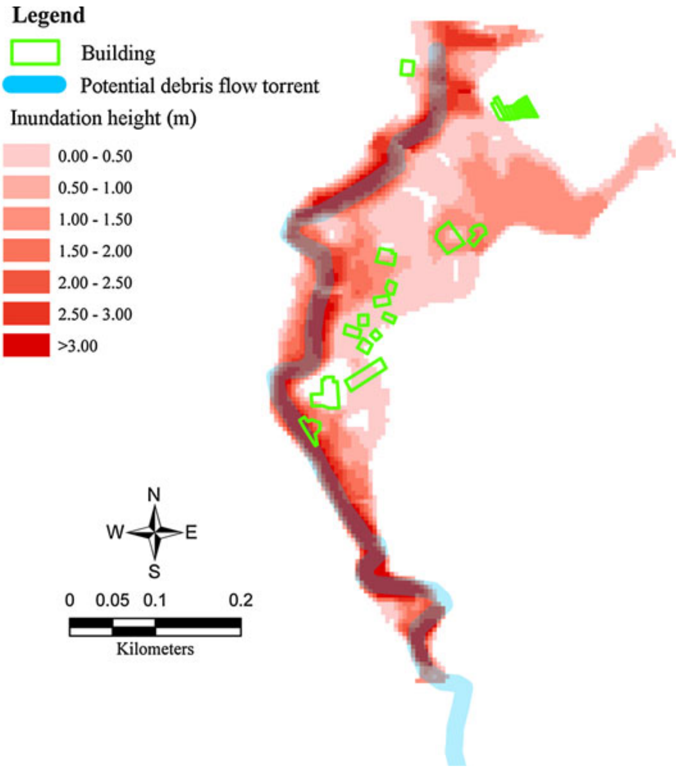


Fig. 2 Simulation result of debris flow occurrence, merged with elements at risk by GIS

Birkmann (2006) recognized the ability to measure vulnerability as an essential prerequisite for reducing disaster risk. Quantifying vulnerability requires both, to identify exposure and to better understand the exposure to hazards of natural origin. For this reason, vulnerability is turning into an essential component for analyzing natural hazard risks and lowering the positive strength between damages and elements at risk. Similarly, Garatwa and Bollin (2002) defined vulnerability as the inadequate means or ability to protect oneself against the adverse impacts of natural events and, on the other hand, to recover quickly from their effects. Alexander (2000) stated that vulnerability refers to the potential for casualty, destruction, damage, disruption or other forms of losses with respect to a particular element at risk. Funneling down to a natural-scientific approach, Buckle et al. (2000) described vulnerability as the degree of loss to a given element at risk or set of such elements resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total loss), or in percentage of the new replacement value in the case of damage to property. Li et al. (2010) explained that for property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost. Given this snapshot it becomes evident that the definitions of vulnerability vary, and no universal terminology exists that per se could fulfill all different aspects of natural sciences and social sciences. In order to have an improved comprehension of vulnerability, Hufschmidt et al. (2005) discussed these two approaches from natural (and engineering) sciences and social sciences to better understand vulnerability and concluded that 'adaptation' and 'adaptive capacity' are key elements of vulnerability, and she demonstrated that 'adaptation' and 'adaptive capacity' serve as hinges not only for conceptualizing vulnerability but between 'vulnerability' and 'resilience' alike (Fuchs et al. 2011). For the quantification of vulnerability to natural hazards, Roberts et al. (2009) considered overall vulnerability with five components including physical, health, economic, administrative and environmental vulnerability.

With respect to mountain hazards and based on the principles of dynamic response of simple structures, Haugen and Kaynia (2008) proposed a method based on HAZUS to predict the damage in a structure impacted by a debris flow of known magnitude. Fuchs et al. (2007) were also focusing on debris flow vulnerability and proposed a vulnerability function from Alpine debris flow data where several brick masonry and concrete construction buildings were damaged by 20,000 m^3 of debris. Their assessment was based on a classification of the loss ratio according to a debris flow intensity of 0.5, 1.0, 1.5, 2.0, and 2.5 m. Totschnig et al. (2011) extended this database by analyzing the records of three torrent processes in the Austrian Alps and derived a quantitative vulnerability function applicable to residential buildings located on torrent fans. Quan Luna et al. (2011) established a debris flow vulnerability function with the data set of brick masonry buildings that was struck by a debris flow in Selvetta, Italy, in 2008. Besides, Huttenlau and Stötter (2011) summarized various vulnerability categories from Wisner (2004), Thywissen (2006) and Fuchs (2009).

Previous studies established vulnerability relationships for buildings affected by debris flows through carefully documented economic loss data or insurance records. In Taiwan, however, data on economic losses as a result of debris flow events or insurance claim information are usually not available. Consequently, a direct connection with intensity data is not feasible due to missing well-documented damage data. Thus, this study aims to propose an alternative approach to establish such a relationship for debris flow events in Taiwan and to connect the occurring damage with elements at risk exposed such as buildings. In this study, vulnerability is defined as the ratio of loss relative to the original value of buildings. In other words, vulnerability of building means the ratio between reconstruction expenses and the original building value.

Taiwan is located in the Western Pacific, with earthquakes and typhoons occurring frequently. From the statistics of the Central Weather Bureau, over the past 50 years there were 4.9 typhoons hitting Taiwan annually (Chen et al. 2011). In the past two decades, debris flow hazards have resulted in tremendous economic loss and casualties. As of May 2011, there were 1,578 potential debris flow torrents enlisted around Taiwan.

In August 2009, Typhoon Morakot hit Taiwan, and more than 2,000 mm of cumulative rainfall was recorded within 3 days (August 07–09). According to the record from the Soil and Water Conservation Bureau (SWCB), which is in charge of the mitigation and management of debris flow hazards, during the typhoon event more than one hundred debris flow events occurred. From the annual report of the SWCB (2010), 24 of the recorded debris flow hazard events resulted in 70 fatalities and 351 damaged buildings (see Fig. 3). However, the inundation heights and the household losses were not recorded. As a consequence, it was not possible to derive the building vulnerability directly. In order to understand the characteristics of buildings in mountain areas, during this study data from 35 debris flow torrents was collected in order to obtain information on losses for ten villages which suffered from debris flows during Typhoon Morakot in 2009 (the locations of these villages are shown in Fig. 4). These data included the geographical position of buildings, their number of storeys and their structure type. Out of these 2,081 buildings, 73 % of the buildings were one-storey structures and 65 % of the buildings were a brick or

Fig. 3 Buildings damaged by debris flows during Typhoon Morakot 2009

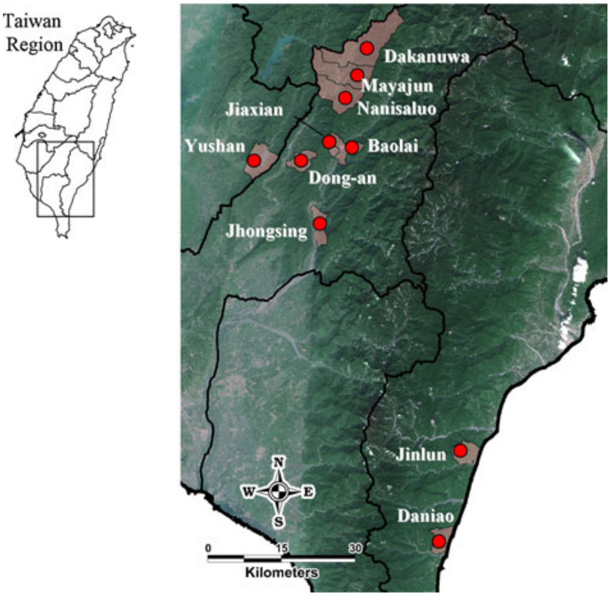


Fig. 4 Location of ten villages selected to collect building data in this study

reinforced brick structure type. Thus, for this study only one-storey brick and reinforced brick structure buildings were considered for the analyses since they represent the typical buildings type in mountain areas of Taiwan. According to these data, the average floor area was approximated with 60 m^2.

From the assessment of the buildings harmed by debris flows in these ten villages, the structures of buildings was generally with minor damages, but the contents were totally lost in most cases, as shown in Fig. 5. Thus, for this study, building vulnerability was defined

Fig. 5 Methodology flowchart of this study to establish the building vulnerability

as the combination of both, reconstruction expenses of the building envelope and the content of the building.

2 Method

In Taiwan, after debris flow events, most damaged buildings are regularly demolished or restored by government or military personnel. The corresponding inundation heights and amount of loss were usually not recorded. Furthermore, housing insurance is not popular, and there is no debris flow-related insurance policy. Therefore, establishing building vulnerability curves from an insurance claim amount—often suggested in order to obtain a damage-depth or vulnerability function, see e.g. Fuchs et al. (2007) and Totschnig et al. (2011)—is not applicable in Taiwan. In order to overcome this gap, a flowchart to evaluate the building reconstruction expenses (Fig. 6) is proposed to establish the building vulnerability function in Taiwan. The building vulnerability discussed here represents the ratio of expected reconstruction expenses to the original building value. The content loss ratio is defined as the ratio between the building content reconstruction expenses for different inundation heights and the total value of the content, as shown in Eq. 3. The structure loss ratio is defined as the ratio between the building structure reconstruction expenses for different inundation heights and the value of structures per m^2, as shown in Eq. 4. Through combining the content and structure parts, the total reconstruction expenses can be obtained. The ratio of total reconstruction expenses to the original building values can be obtained as the building vulnerability (Eq. 5).

$$R_C(h) = \frac{L_C(h)}{U_C} \tag{3}$$

$$R_S(h) = \frac{L_S(h)}{U_S} \tag{4}$$

$$V_B(h) = \frac{L_S(h) \cdot A + L_C(h)}{U_S \cdot A + U_C} \tag{5}$$

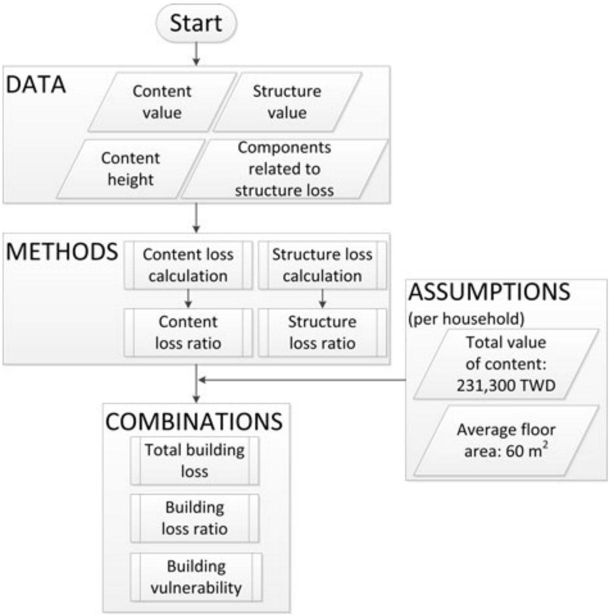


Fig. 6 Content loss induced by debris flows

where h = debris flow inundation height; $R_C(h)$ = content loss ratio; $L_C(h)$ = reconstruction expenses of the content; U_C = total value of the content; $R_S(h)$ = structure loss ratio per m^2; $L_S(h)$ = reconstruction expenses of structures per m^2; U_s = value of structures per m^2; $V_B(h)$ = building vulnerability; and A = floor area equal to 60 m^2. Please note: U_s varies with different structure types.

2.1 Content loss of buildings

When an intrusion of debris flows into buildings is observed, usually the content will be damaged or destroyed. In order to establish the building content loss and the respective loss ratio, the following information is necessary.

2.1.1 Content value

The content of the building include furniture and household facilities. The overall items of content were obtained from the survey of family income and expenditure which was executed by the government of Taiwan (Directorate-General of Budget 2010). In Table 1, the most common items of content in households of Taiwan and the respective costs are provided, the latter being acquired from current market prices.

2.1.2 Content height

In Taiwan the dimensions of household content were proposed for flood damage studies (Chang 2000); in Table 1, the initial and top heights of the most common household content collected for this study are shown.

Table 1 Height of content and price of common content in Taiwan (modified from Chang 2000)

Item	Initial height (cm)	Top height (cm)	Unit price (TWD)
Air conditioner	200	238	28,700
Color TV	65	124	25,500
Dehumidifier	0	60	9,500
Desk light	80	130	900
Dish drier	80	132	3,100
Drier	0	100	5,500
DVD player	65	88	1,300
Electric oven	80	86	1,700
Electric water boiler	80	116	1,900
Exhaust hood	150	171	7,800
Geyser	145	219	6,900
Hot-warm water fountain	80	133	3,900
Mattress	45	55	6,000
Microwave oven	80	112	6,800
Personal computer	80	115	29,600
Refrigerator	0	167	15,300
Roof light	315	325	7,500
Sofa	0	40	32,000
Stereo	65	98	12,000
Telephone	50	55	1,500
Vacuum cleaner	0	39	8,600
Washing machine	0	95	15,300

2.1.3 Content loss calculation

A synthetic approach for content loss calculation was applied in this study due to the incomplete information on past loss data outlined above. This approach involved a synthesis of all available data, from both secondary sources and real experiences. A similar approach has been adopted for flood damage calculation in UK (Messner et al. 2007) and Taiwan (Kang et al. 2005): Flood damage data were built up from an accumulation of knowledge about the effects of floodwater on households and building contents, and the effect on the building envelope including necessary repair and renovation (Messner et al. 2007). Following this approach, content loss was calculated to estimate possible loss as a result of debris flow intrusion taking into account the higher density and flow pressures of debris flows compared to pure inundation. Thus, the contents were considered as a total loss when the magnitude of debris flows exceeded the initial height of contents. Adding the content value from Table 1 with this synthetic approach, the corresponding cumulative loss and the loss ratio for increasing process magnitudes were calculated as shown in Table 2.

2.2 Structure loss of buildings

For debris flow hazards, the degree of loss for the building structure is typically related to building materials used to construct the building envelope (Holub et al. online first). Studying the following, brick and reinforced brick structures will be discussed in detail

Table 2 Cumulated loss and loss ratio at different debris flow inundation heights for common content in Taiwan

Inundation height (m)	Cumulated loss (TWD)	Loss ratio (%)
0	–	0.00
0.1	86,200	37.3
0.2	86,200	37.3
0.3	86,200	37.3
0.4	86,200	37.3
0.5	92,200	39.9
0.6	93,700	40.5
0.7	132,500	57.3
0.8	132,500	57.3
0.9	180,400	78.0
1.0	180,400	78.0
1.1	180,400	78.0
1.2	180,400	78.0
–	–	–
3.2	231,300	100.0
3.3	231,300	100.0
3.4	231,300	100.0
3.5	231,300	100.0

since a major part of buildings in Taiwan are of this type (cf. Introduction). In Taiwan, reinforced brick structures are constructed with 23-cm-thick brick walls and strengthened with reinforced concrete (RC) columns. The RC slab and RC beams are constructed to form a solid structure (Liu et al. 2004). In contrast, brick structures are characterized by a weaker construction type compared to the reinforced brick structures, resulting in less resistance toward compressive and lateral forces (Fig. 7). To establish the building structure loss and the respective loss ratio, the following information was collected.

2.2.1 Structure value

The structure value is generally related to the building usage, the type of construction material, the total floor area, and the number of storeys. Structure costs per m^2 were be obtained from Taiwan Architects Association, as shown as an example in Table 3 for the Kaohsiung region, Taiwan: the structure costs for one-storey buildings composed from brick and reinforced brick are 6,000 TWD (New Taiwan Dollars) and 14,000 TWD per m^2, respectively (1 US Dollar is approximately 30 TWD as of 2011).

2.2.2 Components related to structure loss

In this study, the structure loss was estimated by the reconstruction expenses necessary as a result of different process magnitudes (inundation heights), with an interval of 0.1 m and for different structure material types. The reconstruction expenses included three categories: (1) debris cleaning costs, (2) finishing and painting costs, (3) utilities and openings costs.

Fig. 7 Types of buildings: **a** reinforced brick: brick walls with RC column, beam and slab **b** brick: brick walls

(1) Debris cleaning costs: Debris remaining in the building requires cleaning by personnel; the costs were approximated with 550 TWD per m^2.

(2) Finishing and painting costs: After the cleaning of debris, the interior of buildings is usually treated with mortar finishing and painting. The costs of finishing and painting were approximated with 140 TWD per m^2. To give an example, in the case of a 60 m^2 and one-storey structure, assuming that the length, width and height are 10, 6 and 3.5 m, the area of floor and walls is 172 m^2, which is approximately three times the floor area. As a result, the finishing and painting costs for each meter of debris inundation height are 120 TWD, as shown in Eq. 6.

Table 3 Structure unit cost (simplified version provided by Taiwan Architects Association, 2007)

Structure unit cost, Kaohsiung County, 2007
Unit: TWD/Sq-m

Material	Reinforced concrete Precast concrete			Reinforced brick		Brick
Storey (F)	Type I	Type II	Type III	Storey (F)	All types	All types
1–3	16,800	17,300	18,500	1	14,000	6,000
4–5	17,850	17,900	19,200	2	14,500	–
6–8	18,500	18,800	19,800	3	15,000	–
9–11	19,000	19,300	20,200	4	–	–
12–14	20,300	19,800	20,600	5	–	–
15–17	20,800	20,300	21,000	–	–	–

Type I: office, class room, resident housing, dorm, warehouse

Type II: laboratory, community center, restaurant, clinic

Type III: library, stadium, theater, museum, art gallery

$$\frac{140\ \mathrm{TWD}/\mathrm{m}^2 \times 60\ \mathrm{m}^2 \times 3}{60\ \mathrm{m}^2 \times 3.5\ \mathrm{m}} = 120\ {}^{\mathrm{TWD}}/_{\mathrm{m}^2} \times \mathrm{m} \tag{6}$$

(3) Utilities and openings costs: Debris flows regularly resulted in the destruction of utility systems and building openings such as windows and doors. In Taiwan, utilities and openings costs is about 15 % of the total building structure value (Chung 2010); thus, it was assumed that (a) the maximum loss ratio, which reached 3.5 m, was 15 % of the total structure cost, and (b) the loss ratio increased linearly with the process magnitude (inundation height).

2.2.3 *Structure loss calculation*

From field observation in ten villages, when buildings were harmed by debris flows, there is some evidence that collapsing walls result in high amounts of loss of structures and contents (Fig. 8). From the concept of the panel failure curves for flood depths and velocities, different failure curves corresponded to different properties of block work (Kelman 2002). This concept was adopted by simulating the wall destruction as a result of the impact of debris flows. In Fig. 9, the respective failure curves for brick walls of a one-storey 60 m^2 building under the load of different flow densities and impact forces of debris flows are shown (Wu 2010).

For the case study, a set of debris flow velocities and impact forces was assumed. According to the literature, the velocity of debris flows varies between 2 and 20 m/s (Hürlimann et al. 2003; Zanchetta et al. 2004; Arattano and Marchi 2005). Through an analysis of CCD (charge-coupled device) image camera movies of monitoring stations in Hualien and Nantou, Taiwan, the typical velocity of debris flows was estimated in the range between 8.4 and 10 m/s (Jan 2005; Yin et al. 2006; Ko et al. 2006); hence, for this study, a typical value of debris flow velocity was assumed to equal 9.2 m/s. The flow density and boulder size for debris flow impact force was set at 2,100 $\mathrm{kg/m}^3$ and

Fig. 8 Examples for structural damage assessed during field investigation: **a** when inundation height is ≥2 m, and **b** when inundation height is <2 m

0.3 m, respectively. With the assumed debris flow velocity and impact force (9.2 m/s, 2,100 kg/m^3, 0.3 m), the brick wall will be destroyed when the process magnitude (inundation height) is ≥2 m, and the structure loss will increase rapidly with higher magnitudes. This study, therefore, calculates the loss ratio differently when the process magnitude (inundation height) is <2 and ≥2 m. For brick structures, when inundation heights are <2 m, the structure loss ratio was calculated by Eq. 7 and with a maximum loss ratio of approximately 30 %, as shown in Eq. 8.

$$R_S(h) = \frac{\text{Debris cleaning costs} + \text{Finishing and painting costs}}{\text{Structure unit cost}} + \text{Utilities and openings costs} \tag{7}$$

where h = debris flow inundation height; $R_S(h)$ = structure loss ratio per m^2.

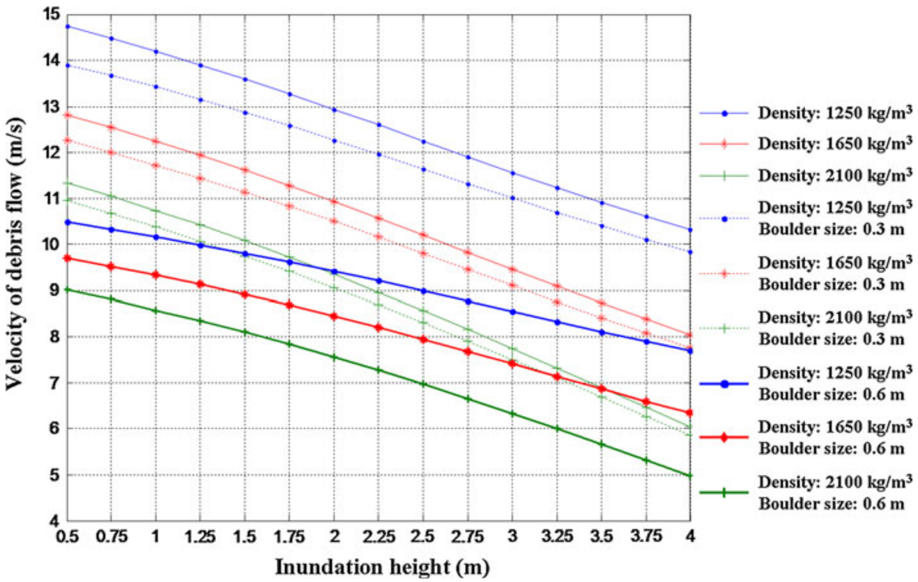


Fig. 9 Failure curve of one-storey brick structure with a floor area of 60 m^2 for different debris flow properties

Equation 8 was applied for brick structures when the inundation height equals 1.9 m:

$$R_S(h) = \frac{550\ \text{TWD/m} \times 1.9\ \text{m} + 120\ \text{TWD/m} \times 1.9\ \text{m}}{6{,}000\ \text{TWD}} + 15\ \% \times {}^{1.9\ \text{m}}\!/_{3.5\ \text{m}} = 29.4\ \% \tag{8}$$

When inundation height was ≥2 m, the structure loss was assumed to increase linearly with the remaining ceiling (Eq. 9).

$$R_S(h) = 0.3 + \frac{0.7}{1.5}(h - 2) \tag{9}$$

For reinforced brick structures, when the inundation height is <2 m, the maximum loss ratio was calculated with 20 % of the total value (Eq. 7). When inundation heights were ≥2 m, the structure loss was expressed by applying Eq. 10.

Table 4 and Fig. 10 summarize and visualize the loss ratio at different inundation heights for brick and reinforced brick buildings.

$$R_S(h) = 0.2 + \frac{0.8}{1.5}(h - 2) \tag{10}$$

3 Results

In the following paragraphs, the results obtained with the presented method are described for the loss ratio of the content of buildings as well as for the building structure, and in combination with respect to the overall vulnerability of buildings.

Table 4 Loss ratio at different debris flow inundation heights for different structural materials

Inundation height (m)	Loss ratio (%)	
	Reinforced brick	Brick
0	0.0	0.0
0.1	0.9	1.6
0.2	1.8	3.1
0.3	2.7	4.6
0.4	3.6	6.2
0.5	4.5	7.7
0.6	5.4	9.3
0.7	6.4	10.8
0.8	7.3	12.4
0.9	8.2	13.9
1.0	9.1	15.5
1.1	10.0	17.0
1.2	10.9	18.5
–	–	–
3.5	100.0	100.0

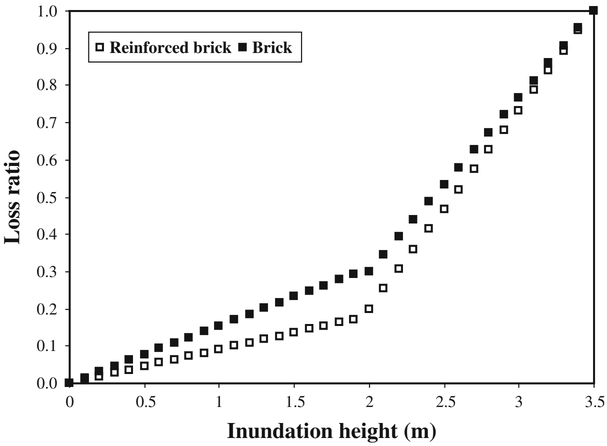


Fig. 10 Structure loss ratio of reinforced brick and brick structures at different inundation heights based on the synthetic approach

3.1 Content loss ratio

Fitting the data presented in Table 2 with respect to the cumulated loss ratio of content, a regression function was established as shown in Eq. 11.

$$R_C(h) = \begin{cases} 0.0583\,h^3 - 0.4281\,h^2 + 1.0806\,h, & \text{if} \quad 0\,\text{m} \le h < 3.2\,\text{m} \\ 1, \quad \text{if} \quad h \ge 3.2\,\text{m} \end{cases} \tag{11}$$

where h = debris flow inundation height; $R_C(h)$ = content loss ratio.

Obviously, no content loss resulted if the debris flow inundation height equaled zero and a total loss resulted if the debris flow inundation height was ≥3.2 m. At 0.5, 1, and 1.5 m, the loss ratios of the content were 44, 71, and 85 %, respectively, as shown in Fig. 11. The

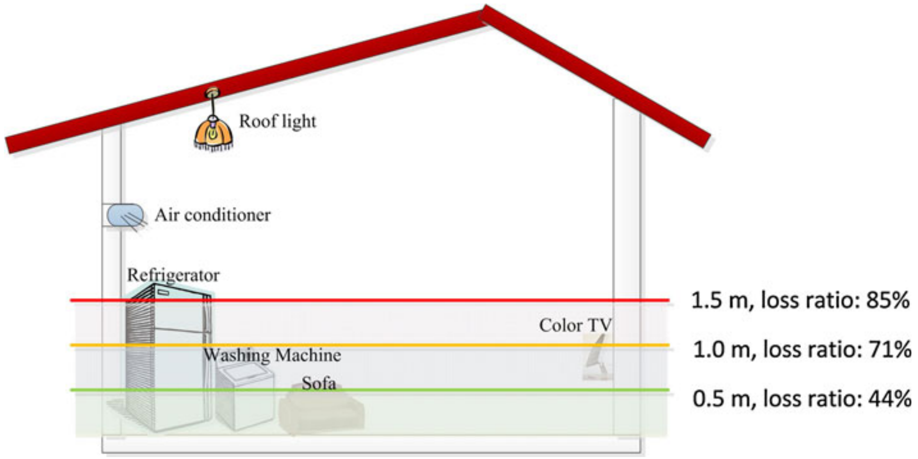


Fig. 11 An example image of content loss

loss ratio increased rapidly at the lower range of inundation height but slowly at the higher range.

3.2 Structure loss ratio

Fitting the data presented in Table 4 with respect to the cumulated loss ratios for brick and reinforced brick structures, the regression functions were established as shown in Eqs. 12 and 13, respectively.

For brick structures:

$$R_S(h) = \begin{cases} 0.0184\,h^3 - 0.0209\,h^2 + 0.1447\,h, & \text{if} \quad 0\text{ m} \le h < 3.43\text{ m} \\ 1, \quad \text{if} \quad h \ge 3.43\text{ m} \end{cases} \tag{12}$$

For reinforced brick structures:

$$R_S(h) = \begin{cases} 0.0218\,h^3 - 0.006\,h^2 + 0.0558\,h, & \text{if} \quad 0\text{ m} \le h < 3.43\text{ m} \\ 1, \quad \text{if} \quad h \ge 3.43\text{ m} \end{cases} \tag{13}$$

where h = debris flow inundation height; $R_S(h)$ = structure loss ratio per m^2.

For brick and reinforced brick, there was no structure loss when debris flow inundation heights equaled zero and total loss occurred when inundation heights were ≥3.43 m. At 1, 2, and 3 m, the loss ratio corresponded to 7, 26, and 70 % for reinforced brick structures, and 14, 35, and 74 % for brick structures. Both structure types have shown the same tendency to develop slowly at lower inundation heights and to develop rapidly at the higher ranges. The loss tendency of structures was opposite to the loss tendency of the content. In general, the loss ratio of brick structures was higher than that of reinforced brick at any inundation height.

3.3 Building vulnerability

We defined building vulnerability as the combination of content loss and structure loss. However, the content loss was calculated based on one household and the structure loss

Table 5 Loss ratio of building for the corresponding debris flow inundation height

Inundation height (m)	Loss ratio (%)	
	Reinforced brick	Brick
0	0.00	0.00
0.1	2.68	4.93
0.2	5.18	9.52
0.3	7.52	13.79
0.4	9.72	17.77
0.5	11.80	21.46
0.6	13.77	24.90
0.7	15.65	28.09
0.8	17.47	31.07
0.9	19.23	33.86
1.0	20.96	36.46
1.1	22.67	38.91
1.2	24.39	41.23
–	–	–
3.5	100.0	100.0

was based on an averaged value per m^2. Thus, in order to combine the two different loss measures into building vulnerability, a floor area of 60 m^2 was introduced in Eq. 5. The results are shown in Table 5, and the regression functions based on the data presented in Table 5 are shown in Eqs. 14 and 15. For reinforced brick and brick buildings, the building vulnerability curves are shown in Fig. 12.

The building vulnerability for brick structure was

$$V_B(h) = \begin{cases} 0.0316\,h^3 - 0.1706\,h^2 + 0.5024\,h, & \text{if} \quad 0\text{ m} \le h < 3.43\text{ m} \\ 1, \quad \text{if} \quad h \ge 3.43\text{ m} \end{cases} \tag{14}$$

and the building vulnerability for reinforced brick structure was

$$V_B(h) = \begin{cases} 0.0266\,h^3 - 0.0848\,\mathrm{h}^2 + 0.2663\,h, & \text{if} \quad 0\text{ m} \le h < 3.43\text{ m} \\ 1, \quad \text{if} \quad h \ge 3.43\text{ m} \end{cases} \tag{15}$$

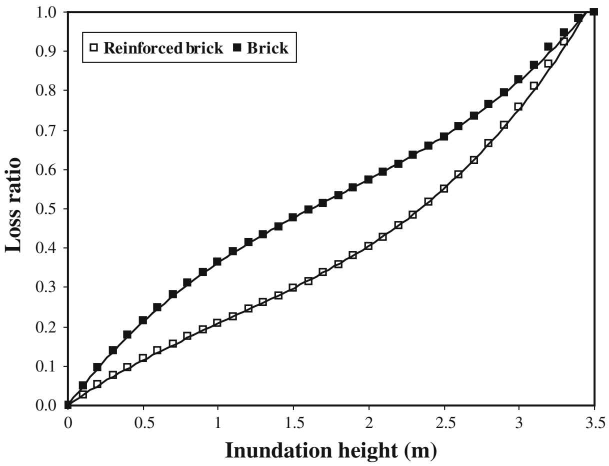
where h = debris flow inundation height; $V_B(h)$ = building vulnerability.

For the building vulnerability of brick and reinforced brick structures, there was no loss when debris flow inundation heights equaled zero and total loss occurred when inundation height were $\ge$3.43 m. At 1, 2, and 3 m, the loss ratio corresponded to 21, 41, and 75 % for reinforced brick structures, and 36, 58, and 83 % for brick structures. The loss ratio increased with the process magnitude (proxied by the inundation height). Furthermore, due to the opposite development tendencies for loss ratios of content and structure, the building vulnerability gently rose, compared with structure loss ratio. In general, reinforced brick buildings were less vulnerable than brick buildings.

4 Discussion and conclusion

Following the concept of reconstruction expenses, this study proposed a debris flow vulnerability function for buildings exposed to debris flows. This vulnerability function may

Fig. 12 Loss ratio of building including content and structure loss for reinforced brick and brick structures at different inundation heights and their vulnerability curves



be used for risk analyses in Taiwan since it had been shown that the application of methods developed in other environmental settings may be misleading (Fuchs et al. in press). The content and structure loss of buildings were calculated separately to more precisely analyze the possible losses, which were corresponding to debris flow magnitudes proxied by inundation heights. With different inputs regarding structures and content losses, the approach this study proposed provided an option for regions without proper historical data on debris flow loss or missing event documentation. The proposed approach is also applicable to regions with different economic activities, different building types or building materials, and different structure types and content values of buildings, which makes the establishment of building vulnerability more flexible. When merging the elements at risk (exposure) with different return periods of hazard processes and building vulnerability functions, debris flow risk can be calculated for individual torrent catchments; which can be further utilized in risk ranking and risk management options.

However, with multiple input data of structure and content loss ratio, the variables may be a subject to further in-depth studies and future adjustments. A comparison of vulnerability values and functional relationships between this study and Fuchs et al. (2007) has shown similarities and differences (Fig. 13 and Table 6); hence, approaches from different regions and with respect to different environmental settings still have potential for harmonization with respect to different approaches, regions, and data sets. In our study, vulnerability reached a value of 1 (total damage) at 3.43 m, while the curve from Fuchs et al. (2007) showed a strong increase and reached the total damage threshold at a process magnitude of approximately 3.11 m. In general, the curves from both studies reach the threshold of total damage due to the impact of debris flows within a similar range of magnitude between 3 m and 3.43 m.

In the lower part of the curves, especially for process magnitudes between 0 and 1 m, the two curves (for both brick and reinforced brick) from our study showed the highest loss ratio compared with the studies of Fuchs et al. (2007). This may be an artifact because the content loss ratio already reached 71 %, which contributed to the large loss in this range of magnitude. When the debris flow magnitude was between 1 and 2 m, the vulnerability curves from Fuchs et al. (2007) increased faster and were equal to or surpassed the curves from our Taiwanese study. This is a result of our method applied since beyond a process magnitude of 1 m, the contribution of content loss relatively decreased. In Taiwan, the

Fig. 13 Comparison of building vulnerabilities presented as loss ratio depends on inundation height between Fuchs et al. (2007) and this study (reinforced brick and brick)

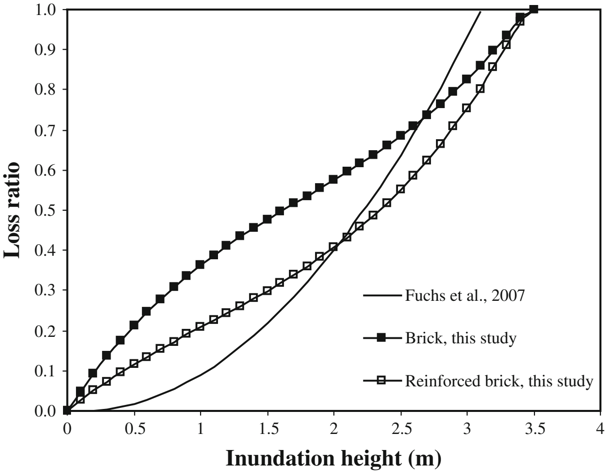


Table 6 Comparison of building vulnerability (loss ratio) between Fuchs et al. (2007) and this study (brick and reinforced brick)

Inundation height (m)	Loss ratio (0–1)		
	Fuchs et al. (2007)	This study	
		Reinforced brick	Brick
0.0	0	0	0
0.5	0.0175	0.1153	0.2125
1.0	0.090	0.2081	0.3634
1.5	0.2175	0.2984	0.4764
2.0	0.4000	0.4062	0.5752
2.5	0.6375	0.5514	0.6835
3.0	0.9300	0.7539	0.8250
3.5	1	1	1

percentage of building content value is generally higher compared to European regions; hence, for an average 60-m^2 one-storey brick building, the content value was approximately 40 % of the sum of structure value (360,000 TWD) and content value (231,300 TWD), which may explain the higher contribution of loss ratio at the lower process magnitude. However, with the synthetic approach developed, it was assumed that the debris penetrated the building envelope, which may not be true during every event and may therefore result in the overestimation of vulnerability in this study.

Considering the available data in Taiwan and the limitations introduced, some assumptions were made in this study for establishing the building vulnerability to debris flows. Nevertheless, the concept and method proposed by this study provided an alternative approach for understanding building vulnerability to debris flows. In order to improve and validate the methodology as well as the results, more investigation and the concise collection of loss information after every future debris flow event should be conducted. Inundation height of debris flows was the most available data for vulnerability analysis in many studies. However, the damage to the buildings was not contributed only by inundation height; further studies considering other physical properties should be introduced in order to improve the understanding of vulnerability.

Fuchs (2009) determined that the connection between social vulnerability and structure vulnerability is monetary and that understanding monetary losses would be the first step to understand the natural hazard impact on individual households and on society. A debris flow hazard of the same magnitude and frequency will contribute differently to the amounts of structural and content loss for different regions and within different countries. This study provides a concept for analyzing debris flow hazards and building losses according to different categories to better understand the vulnerability. The ability to recover, measured in a monetary value, will provide information on vulnerability which will become important for future—also socio-scientific—research.

Acknowledgments This work was funded by the Soil and Water Conservation Bureau of Taiwan. The authors would like to thank S. Fuchs as well as three anonymous reviewers for their valuable comments on an earlier draft of this paper.

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