

Debris-flow building damage level and vulnerability curve – A case study of a 2015 Typhoon event in northern Taiwan

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Abstract

Physical vulnerability of the building is the key element for debris-flow hazard Quantitative Risk Analysis (QRA). Most vulnerability curves were related to the deposition height (Fuchs et al., 2007; Lo et al., 2012), or the combination of deposition height, velocity, and impact force (Quan Luna et al., 2011; Jakob et al., 2012; Kang and Kim, 2016). This study uses datasets obtained from a debris-flow hazard caught on video in northern Taiwan during a 2015 Typhoon event and compare with the existing building damage classes and vulnerability curves. The deposition heights, ranging from 0.1 to 5-m, and damage levels of the 15 houses were carefully documented. Of these 15 reinforced-concrete, reinforced-brick, and brick houses, 7 were considered as totally destroyed judging by their actual damage level, others sustained various damages. The debris-flow velocity and impact force were simulated with RAMMS::DebrisFlow module using inputs of the event and compared with the aftermath inundation range and velocity captured in a live video. It shows that when the information of velocity is unavailable, using deposition height alone could also lead to a reasonable result.

Keywords: Vulnerability; debris-flow; Taiwan; damage classification

1. Introduction

Debris flow has been one of the most devastating sediment disasters in mountainous area; the direct and indirect damages caused by debris flow have cost tremendous economic losses and great casualties worldwide, statistical analysis indicates that debris flow is responsible for 165 fatalities annually around the world (Dowling and Santi, 2014). In Taiwan, the steep terrain, frequent occurrence of earthquake and heavy rainfall has made debris flow a major natural hazard in the mountains (Cheng et al., 2005; Lo et al., 2012; Tsao et al., 2018). To reduce and mitigate hazard risks to the society, the understanding of vulnerability to the elements at risk become an important issue (Fuchs et al., 2012).

1.1. Natural hazard risk and vulnerability

In the conceptual natural hazard risk equation $Risk=Hazard\times Exposure\times Vulnerability$ the vulnerability representing one of the key components, and for debris flow the risk is usually expressed as the loss of life or economic (Jakob et al., 2012). In UNDR0's definition, vulnerability is defined as "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)" (UNDR0, 1979), and could be evaluated as "the interaction between the intensity of the hazard and the type of elements at risk" (Corominas et al., 2014; Blahut et al., 2014).

In this study we focused on the physical vulnerability of debris flow, which was stated by Fuchs et al. (2007) as the damage ratio between the losses of the individual reinstatement value for each element at risk and its original

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value under given debris-flow deposition height. Detailed field survey and aftermath loss monetary value, either from official estimation or insurance claims, were required to generate the vulnerability curve. However, in many regions around the world the insured losses are not available (Jakob et al., 2012; Lo et al., 2012), using damage level or damage classes by expert judgment to define the corresponding vulnerability under different damage conditions provided a surrogate solution (Jakob et al., 2012; Guillard-Gonçalves et al., 2016; Kang and Kim, 2016).

Several studies focused on developing vulnerability curve under the corresponding value of deposition height, flow velocity, or flow pressure in different region (Quan Luna et al., 2011; Lo et al., 2012; Jakob et al., 2012; Totschnig and Fuchs, 2013; Kang and Kim, 2016; Prieto et al., 2018). This study conducted field survey of a debris-flow event which destroyed and damaged several houses in northern Taiwan to determine the building damage levels and deposition height, also the analysis of the live video made the comparison of numerical simulation result with actual event available.

1.2. Purpose

The applicability of vulnerability curves was verified from post-disaster datasets (Papathoma-Köhle et al., 2017), with the curves available, the result could be applied to other regions which do not have complete dataset or not yet struck by debris flow. Using numerical simulation could provide a designated disaster scenario for disaster risk reduction planning, however a validation of the simulation parameters need to be setup. With the above mentioned information available, the quantitative risk analysis of debris flow hazard could be achieved.

2. Study Area

Heliu Community is located in Fuxing Township of Taoyuan County, northern Taiwan. The small community with 30~40 residents is located at the mouth of a potential debris-flow torrent (enlisted as Taoyuan DF034) (Fig 1(a)). Of the 15 residential houses in the community, 4 were built of reinforced concrete, 7 reinforced brick, 2 were brick, and 2 were metal sheet structure. Regarding the storey of the buildings, 12 out of 15 were one-storey and 3 were two-storey buildings, the percentage of building structure and number of storey are in consistent with the findings in Lo et al. (2012). The distribution of these 15 houses is shown in Fig 1(b).

Between 1996 and 2004 three debris-flow events with minor damage were recorded in Heliu Community. The basic information of Taoyuan DF034 is shown in Table 1. In the early morning (approx. 07:45) of Aug. 8, 2015 when Typhoon Soudelor strike Taiwan, the heavy rainfall triggered a landslide in the torrent catchment, the debris were transported down and became debris flow, which damaged 15 residential houses in the community. It is estimated that 13,000 m³ of debris was transported down and deposited in the community, the debris covers almost 8,000 m² with maximum deposition height exceed 5 meters (Lee et al., 2016). The pre and post event views of the deposition zone are shown in Fig 2.

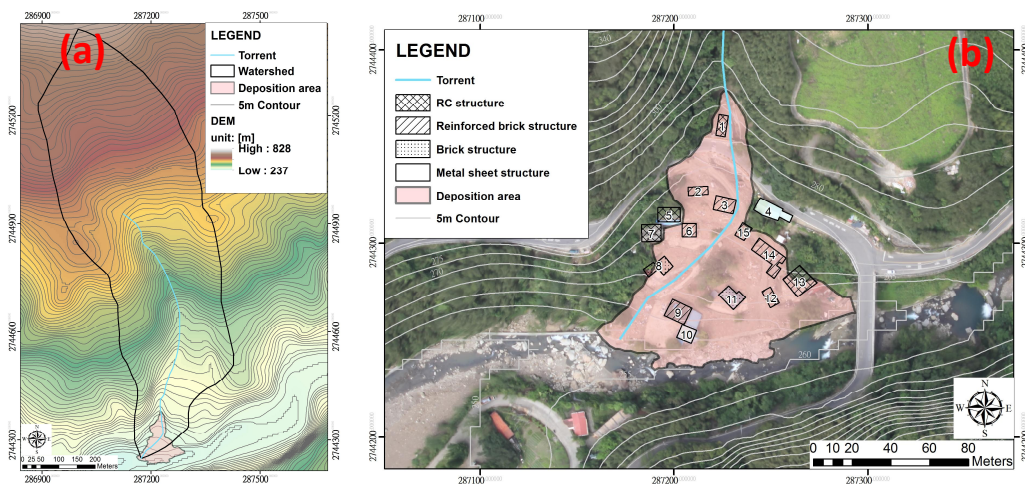


Fig. 1. (a) Catchment topographic map of the study area; (b) Classification and distribution of the 15 houses in the Heliu Community

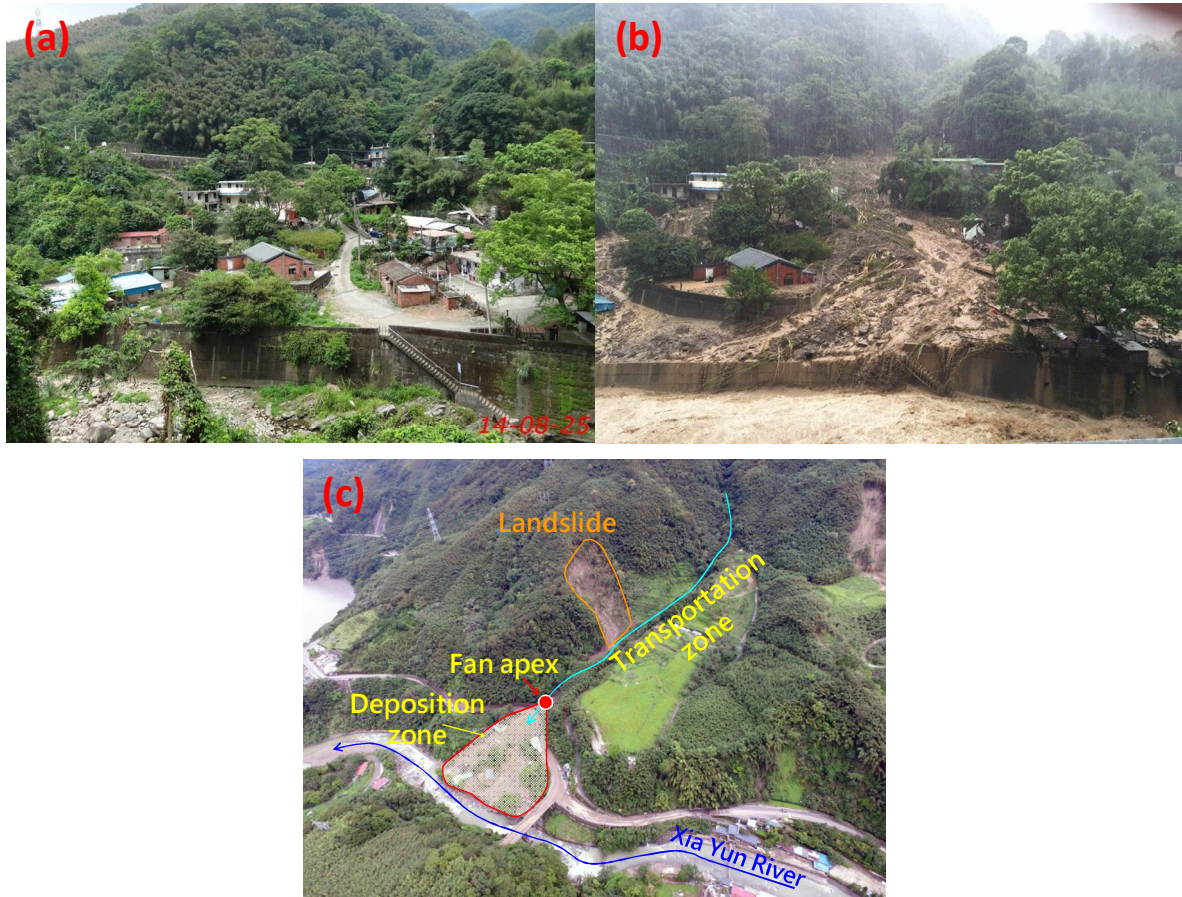


Fig. 2. View of the Heliu Community (a) before the event; (b) during the event; (c) UAV photo after the event (photo: Tsao, T.C. and SWCB)

Table 1. Basic information of Taoyuan DF034 potential debris-flow torrent

Name	Length (m)	Catchment area (ha)	Average slope (°)	Head slope (°)
Taoyuan DF034	759	34	18	30~50

3. Methodology and results

3.1. Damage classification

The damage degree of the 15 buildings in Heliu Community were determined from the field survey two days after the event, the types of building structure, interior and external damage status were carefully checked and documented (Fig 3). As the actual monetary or insured losses were unavailable, this study applies the damage classification to further analysis the vulnerability of the building.

Two methods to determine building damage level were applied in this study. Based on previous studies Guillard-Gonçalves et al. (2016) divided the damage level of the building into 5 classes: negligible damage, slight damage, significant damage, severe damage, and very severe damage, each class with a corresponding range of loss ratio. The estimated loss ratio of buildings in Heliu Community applying this method is shown in Table 2 and Fig 4.

Jakob et al. (2012) classified the damage of buildings into 4 categories (some sedimentation, some structural damage, major structure damage, and complete destruction), with damage description in each category. The result of applying this method is shown in Table 2. In total 7 buildings were considered as complete destruction (IV), 1 as

major structural damage (III), 5 as some structural damage (II), and 2 with some sedimentation (I), some of the damaged buildings and their corresponding damage classes were shown in Fig 3.

The loss ratio of the 15 buildings were plotted on Fig 5 together with vulnerability curves from Fuchs et al. (2007) and Lo et al. (2012), of the 15 plots on Fig 5, more than half of the data sets fall within or close to these 3 curves. In a closer look, reinforced brick and reinforced concrete (R.C.) building were destroyed (loss ratio 1.0) when deposition height is greater than 3.5 m, data sets from reinforced brick buildings fits best to the existing curves, indicates that using deposition height to estimate loss ratio is still a robust but feasible approach.

Table 2. Helio Community building structure information and damage class

Building ID	Building structure	Storey(s)	Loss ratio	Damage class (Guillard-Gonçalves et al., 2016)	Damage class (Jakob et al., 2012)
#1	R.C.	2	1	5	IV
#2	Rein. brick	1	1	5	IV
#3	Rein. brick	1	1	5	IV
#4	Metal sheet	1	0.1	1	I
#5	R.C.	2	0.3	2	II
#6	Rein. brick	1	0.7	4	II
#7	R.C.	2	0.2	1	I
#8	Brick	1	0.5	3	II
#9	Rein. brick	1	0.4	2	II
#10	Metal sheet	1	1	5	IV
#11	Brick	1	0.4	2	II
#12	Rein. brick	1	1	5	IV
#13	R.C.	1	0.8	4	III
#14	Rein. brick	1	1	5	IV
#15	Rein. brick	1	1	5	IV



Fig. 3. Damaged building and damage class applying Jakob et al. (2012) method: (a) #4, metal sheet structure with damage class I; (b) #11, brick structure with damage class II; (c) #13, reinforced concrete structure with damage class III (photo: Hsu, C.H.)

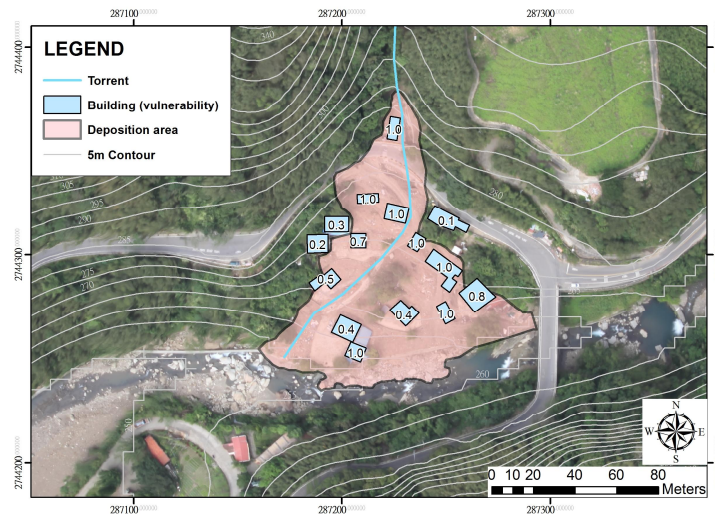


Fig. 4. Loss ratio of the 15 residential houses in the Heliu Community

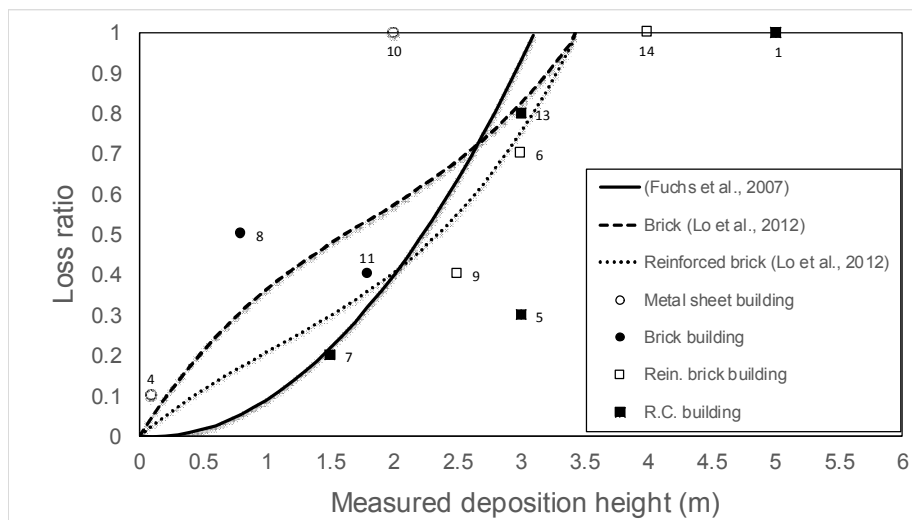


Fig. 5. Comparison of loss ratio with previous studies using deposition height

3.2. Debris-flow numerical simulation

In this study the RAMMS module was applied for debris-flow numerical simulation. The RAMMS (Rapid Mass Movement Simulation) software was developed by WSL (Swiss Federal Institute for Forest, Snow and Landscape Research) for avalanche, rockfall, and debris-flow numerical simulation (Bartelt et al., 2012; Hussin et al., 2012; Leine et al., 2013). The RAMMS::DebrisFlow module is designed for flow phenomena containing fast move particulate debris. The model is based on 2-D depth-averaged shallow-water equations for granular flows in three dimensions given by the coordinates of the topographic surface of the digital elevation model in a (x,y,z) coordinate system and at time (t), for more information about the module one could refer to WSL (2017) or Frank et al. (2017).

The debris-flow numerical simulation and back calculation of Heliu Community debris-flow event were conducted by Lee et al. (2016) and Huang et al. (2018), using RAMMS::DebrisFlow and compared with the live video captured during the event. Through comparing with the actual event shows that in debris coverage area, deposition height, and flow velocity good result could be observed, with average deviation around 24%, 2 to 10%,

and 3 to 12% respectively (Lee et al., 2016), the simulated deposition height compared with field measurement is shown in Fig 7, The input parameters of the RAMMS simulation are listed in Table 3.

The simulation result, include flow height (Fig 6a) and flow velocity (Fig 6b), was extracted and stored in each cell, with this information available, the intensity index (I_{DF}) and damage probability (P_{DF}) proposed by Jakob et al. (2012) could be calculated. I_{DF} is the product of maximum expected flow height (d) and the square of the maximum flow velocity (v), in some studies I_{DF} is also refer as momentum flux (Jakob et al., 2012; Prieto et al., 2018).

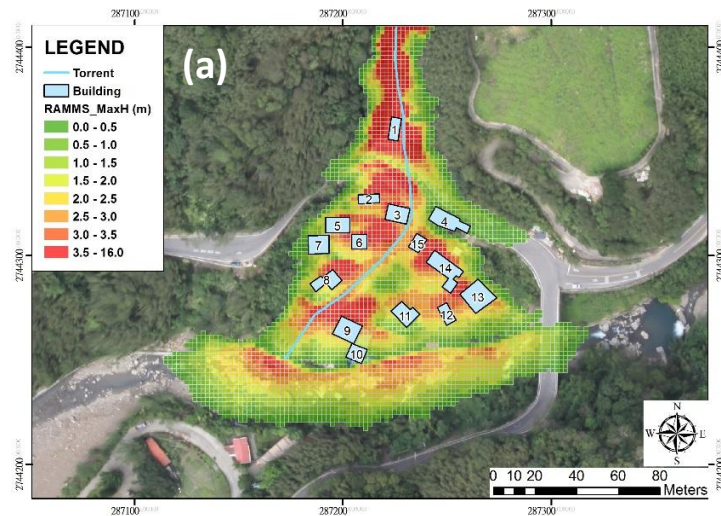
Using the abovementioned simulation result and adopting statistic result of damage probability from Jakob et al. (2012), the estimated number of houses in each damage class is calculated and listed next to the actual losses, as shown in Table 4. The differences in I, II, III, and IV classes were 0% (match), 20%, 75%, and 29% respectively.

Table 3. The input parameters for RAMMS simulation (after Lee et al., 2016; Huang et al., 2018)

Parameter	Input
Terrain (DEM)	2m*2m
Landslide area (m ²)	5,736
Average thickness of landslide (m)	4.7
Block release volume (m ³)	26,966.7
Density (kg/m ³)	1,920
Dry-Coulomb type friction (dimensionless)	0.24
Viscous-turbulent friction (m/s ²)	300
Simulation duration (hr)	3

Table 4. Damage probabilities for Helio Community and the total number of houses affected

I_{DF}	Number of houses affected	I(%)	II(%)	III(%)	IV(%)
0~1	2	70	30	0	0
1~10	3	22	50	22	6
10~100	4	0	37	38	25
100~1,000	6	0	5	28	67
>1,000	0	0	0	0	100
Calculated result (round to integer)		2.06 (2)	3.88 (4)	3.86 (4)	5.20 (5)
Actual damage class (from Table 2)		2	5	1	7



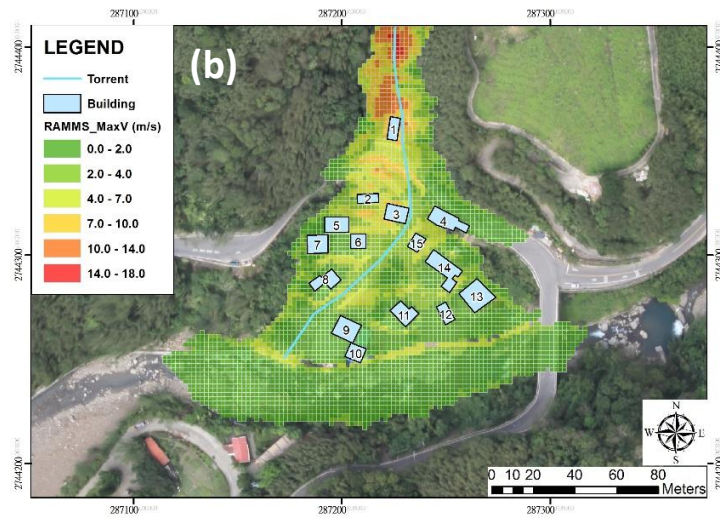


Fig. 6. (a) Maximum flow height of RAMMS simulation; (b) Maximum flow velocity of RAMMS simulation (modified from Huang et al., 2018)

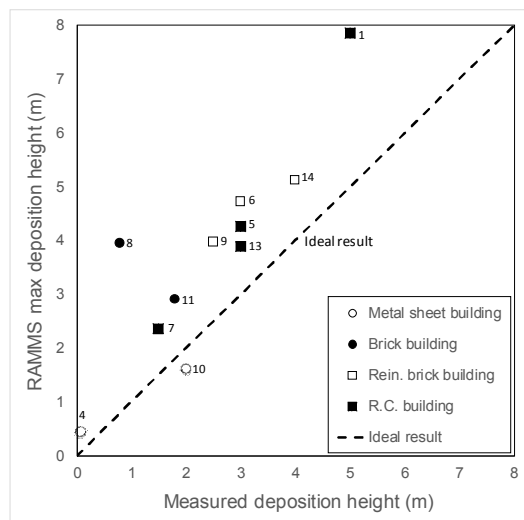


Fig. 7. Comparison of RAMMS simulation result with field measured deposition height

4. Conclusion

Two types of damage classes from debris-flow impact were utilized in a detailed-documented and simulated debris-flow event in northern Taiwan, the result was compared with existing vulnerability curves and intensity index. It shows that alone using deposition height to estimate the loss ratio through existing vulnerability still remain as a simple but feasible method. Also considering flow velocity or impact force might be a promising solution when data were available.

However, users should keep in mind that all vulnerability curves, matrices and indicators, or numerical simulation models have their limitations according to their assumptions, original datasets, inputs and parameters (Nakatani et al., 2013; Papathoma-Köhle, 2016; Papathoma-Köhle et al., 2017), thus more understanding about the characteristic of vulnerability is needed (Fuchs et al., 2012).

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References

- Bartelt, P., Bühler, Y., Buser, O., Christen M., and Meier, L., 2012, Modeling mass-dependent flow regime transitions to predict the stopping and depositional behavior of snow avalanches: *Journal of Geophysical Research*, 117, F01015, doi: 10.1029/2010JF001957.
- Blahut, J., Glade, T., and Sterlacchini, S., 2014, Debris flows risk analysis and direct loss estimation: the case study of Valtellina di Tirano, Italy: *J. Mt. Sci.*, 11(2), p. 288-307, doi: doi.org/10.1007/s11629-013-2806-2.
- Cheng, J.D., Huang, Y.C., Wu, H.L., Yeh, J.L., and Chang, C.H., 2005, Hydrometeorological and landuse attributes of debris flows and debris floods during typhoon Toraji, July 29–30, 2001 in central Taiwan: *Journal of Hydrology*, 306(1-4), p.161-173, doi: doi.org/10.1016/j.jhydrol.2004.09.007
- Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., and Smith, J. T., 2014, Recommendations for the quantitative analysis of landslide risk: *Bull Eng Geol Environ*, 73(2), p. 209-263, doi: doi.org/10.1007/s10064-013-0538-8.
- Dowling, C.A. and Santi, P.M., 2014, Debris flows and their toll on human life: a global analysis of debris-flow fatalities from 1950 to 2011: *Nat Hazards*, 71(1), p. 203-227, doi: doi.org/10.1007/s11069-013-0907-4.
- Frank, F., McArdell, B.W., Oggier, N., Baer, P., Christen, M., and Vieli, A., 2017, Debris-flow modeling at Meretschibach and Bondasca catchments, Switzerland: sensitivity testing of field-data-based entrainment model: *Nat. Hazards Earth Syst. Sci.*, 17, p. 801-815, doi: doi.org/10.5194/nhess-17-801-2017.
- Fuchs, S., Heiss, K., and Hübl, J., 2007, Towards an empirical vulnerability function for use in debris flow risk assessment: *Nat. Hazards Earth Syst. Sci.*, 7(5), p. 495–506, doi: doi.org/10.5194/nhess-7-495-2007.
- Fuchs, S., Birkmann, J., and Glade, T., 2012, Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges: *Nat Hazards* 64(3), p. 1969-1975, doi: doi.org/10.1007/s11069-012-0352-9
- Guillard-Gonçalves, C., Zêzere, J. L., Pereira, S., and Garcia, R. A. C., 2016, Assessment of physical vulnerability of buildings and analysis of landslide risk at the municipal scale: application to the Loures municipality, Portugal: *Nat. Hazards Earth Syst. Sci.*, 16, 311-331, doi: doi.org/10.5194/nhess-16-311-2016.
- Huang, C.Y., Hsu, C.H., and Tsao, T.C., 2018, Analysis and comparison of two debris flow numerical simulation models – A case study of a debris flow hazard event: *Sinotech Engineering*, 141, p. 45-55 (in Chinese).
- Hussin, H.Y., Quan Luna, B., van Westen, C.J., Christen, M., Malet, J.P., and van Asch, Th. W.J., 2012, Parameterization of a numerical 2-D debris flow model with entrainment: a case study of the Faucon catchment, Southern French Alps: *Nat. Hazards Earth Syst. Sci.*, 12, p. 3075-3090, doi: doi.org/10.5194/nhess-12-3075-2012.
- Jakob, M., Stein, D., and Ulmi, M., 2012, Vulnerability of buildings to debris flow impact: *Natural Hazards*, 60(2), p. 241-261, doi: doi.org/10.1007/s11069-011-0007-2.
- Kang, H. and Kim, Y., 2016, The physical vulnerability of different types of building structure to debris flow events: *Nat Hazards*, 80(3), p. 1475-1493, doi: doi.org/10.1007/s11069-015-2032-z.
- Lee, C.F., Chou, H.T., Tsao, T.C., Hsu, C.H., Huang, C.H., and Liao, W.S., 2016, Heliu debris flow induced by Typhoon Soudelor: Failure mechanism and numerical simulation: *Journal of Chinese Soil and Water Conservation*, 47 (4), p. 171-184 (in Chinese).
- Leine, R.L., Schweizer, A., Christen, M., Glover, J., Bartelt, P., and Gerber, W., 2013, Simulation of rockfall trajectories with consideration of rock shape: *Multibody System Dynamics*, 32(2), p. 241-271, doi: doi.org/10.1007/s11044-013-9393-4.
- Lo, W.C., Tsao, T.C. and Hsu, C.H., 2012, Building vulnerability to debris flows in Taiwan - a preliminary study: *Natural Hazards*, 64(3), p. 2107-2128, doi: doi.org/10.1007/s11069-012-0124-6.
- Nakatani, K., Okuyama, Y., Hasegawa, Y., Satofuka, Y., and Mizuyama, T., 2013, Influence of housing and urban development on debris flow flooding and deposition: *J. Mt. Sci.*, 10(2), p. 273-280, doi: doi.org/10.1007/S11629-013-2507-x.
- Papathoma-Köhle, M., 2016, Vulnerability curves vs. vulnerability indicators: application of an indicator-based methodology for debris-flow hazards: *Nat. Hazards Earth Syst. Sci.*, 16, p. 1771-1790, doi: doi.org/10.5194/nhess-16-1771-2016.
- Papathoma-Köhle, M., Gemb, B., Sturm, M., and Fuchs, S., 2017, Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flows: *Earth-Science Reviews*, 171, p. 272-288, doi: doi.org/10.1016/j.earscirev.2017.06.007.
- Prieto, J.A., Journeay, M., Acevedo, A.B., Arbelaez, J.D., and Ulmi, M., 2018, Development of structural debris flow fragility curves (debris flow buildings resistance) using momentum flux rate as a hazard parameter: *Eng. Geol.*, 239, p. 144-157, doi: doi.org/10.1016/j.enggeo.2018.03.014
- Quan Luna, B., Blahut, J., van Westen, C. J., Sterlacchini, S., van Asch, T. W. J., and Akbas, S. O., 2011, The application of numerical debris flow modelling for the generation of physical vulnerability curves: *Nat. Hazards Earth Syst. Sci.*, 11, p. 2047-2060, doi: doi.org/10.5194/nhess-11-2047-2011.
- Totschnig, R. and Fuchs, S., 2013, Mountain torrents: quantifying vulnerability and assessing uncertainties: *Eng. Geol.*, 155, p. 31-44, doi: doi.org/10.1016/j.enggeo.2012.12.019.
- Tsao, T.C., Huang, C.Y., Chien, J.H., Yin, H.Y., and Chen, C.Y., 2018, Comparison of debris flow hazard mapping between empirical function and numerical simulation - a case study in Taiwan: In: Yamada, T. et al. (eds.): *Symposium Proceedings of INTERPRAEVENT 2018 in the Pacific Rim, Toyama, Japan, Oct.1–Oct.4, 2018*, pp. 349-354.
- UNDRO (United Nations Disaster Relief Coordinator), 1979, *Natural disasters and vulnerability analysis in report of expert group meeting*. UNDRO, Geneva, Switzerland.
- WSL, 2017, *RAMMSS::DEBRISFLOW User Manual v1.7.0*, Switzerland.