Quantitative Risk Assessment of Debris Flow in Regional Scale

Évaluation quantitative des risques de débris à l'échelle régionale

Gou-Moon Choi
Advanced Infrastructure Research Team, Korea Railroad Research Institute, Korea

Chan-Young Yune
Department of Civil Engineering, Gangneung-Wonju National University, Korea, yune@gwnu.ac.kr

ABSTRACT: Many landslide and debris flow events occur during the summers in Korea, because more than 70% of the country is mountainous in nature and most annual precipitation occurs during this season. Because previous studies on debris flow have focused on identifying the characteristics of debris flows and hazard areas, the demand for studies on methods for determining the priority of measures for preventing debris flows has increased. In this study, a framework for assessing the quantitative risk of a debris flow hazard on the regional scale was suggested and applied to Yongin City, Korea. Based on the return period of rainfall in the region, a numerical simulation was performed, and the vulnerability of each building in the studied area was estimated based on the depth and velocity of potential debris flows. The risk was then assessed in terms of direct costs at both local and regional scales. The shadow angle, which is defined as the angle between the initiation and deposition locations of debris flows, was also estimated. Based on a quantitative risk assessment, the priority of the city's least populous district, Wonsam-myeon, was raised to the second position as the return period of rainfall was increased. Therefore, the quantitative risk assessment method may be a potentially useful tool for assisting in decision-making for the effective planning of hazard prevention by local governments.

RÉSUMÉ : De nombreux glissements de terrain et de débris se produisent pendant les étés en Corée. Car plus de 70% du territoire coréen sont montagneux, et que la plupart des précipitations annuelles se produisent au cours de cette saison. Comme les études antérieures sur la lave torrentielle se sont concentrées sur l'éclaircissement des caractéristiques des laves torrentielles et des zones de risque, il est temps de faire des recherches sur la priorité des mesures de prévention de la lave torrentielle. Dans cette étude, nous cherchions à présenter un modèle pour évaluer le risque quantitatif des agents de production de la lave torrentielle, selon l'échelle des régions, et à l'appliquer à la ville Yongin, en Corée. Sur la base de la période des précipitations dans la région, une simulation numérique a été effectuée et la vulnérabilité de chaque bâtiment dans la zone étudiée a été estimée en fonction de la profondeur et de la vitesse des laves torrentielles potentielles. Le risque a ensuite été évalué en termes de coûts directs aux échelles locale et régionale. Nous avons également estimé l'angle d'ombre, qui est défini comme l'angle entre les emplacements d'initiation et de dépôt des laves torrentielless. Sur la base d'une évaluation quantitative des risques, c'est la commune Wonsaman le moins peuplé de la ville qui a été portée à la deuxième position. C'est parce que la période des précipitations a été augmentée dans cette commune. Par conséquent, la méthode d'évaluation quantitative des risques peut être un outil potentiellement utile pour que les gouvernements locaux décident de faire un plan efficace de prévention des risques de lave torrentielle.

KEYWORDS: quantitative risk assessment, return period of rainfall, shadow angle, regional scale.

1 INTRODUCTION

Many landslide and debris flow events occur during the summers in Korea, because more than 70% of the country is mountainous in nature and most annual precipitation occurs during this season. Localized heavy rainfall also has increased in recent years, especially in the summer, which is the rainy season in Korea. Recently, debris flow hazard at Mt. Umyeon in 2011 (Yune et al., 2013) caused widespread public alarm. After that event, many researches on the risk assessment and mitigation measures against debris flow hazard have begun as a national project in Korea.

So far, studies on debris flow risks can be categorized as a hazard assessment for the evaluating of initiation locations and damaged areas, a vulnerability assessment for the identifying the degree of damage of elements at risk, and a consequence assessment for the estimating direct and indirect economic losses. Melelli and Taramelli (2004) calculated an index based on allocated scores of various factors related to the occurrence of debris flows. Also, they identified debris flow susceptible areas based on the index using a digital elevation model at Terni basin, Italy. Simoni et al. (2011) estimated debris flow volume through back analysis using DFlowz program for deposition area of debris flow in northeastern Italy and analyzed topography using a high resolution LiDAR data. They concluded that the mobility of debris flow depended on a debris flow volume, an inundation area, and a cross-sectional area. Haugen and Kaynia (2008) suggested a vulnerability assessment model for structures impacted by a debris flow based on the dynamic response to earthquake in HAZUS-MH developed by FEMA. Ciurean et al. (2014) performed dynamic run-out modelling and interpreted aerial photographs at the Fella River basin in eastern Italy where experienced severe debris flow hazards in 2003 and developed the vulnerability curve of structure considering depth and height of debris flows. Ghosh et al. (2012) assessed the risk of landslides in Darjeeling Himalayan region of India and estimated the risk in the classification of minimum, medium, and maximum based on the past rainfall record. However, because most of the debris flow research merely classified the hazardous area or evaluated the risk only for the local area, it is necessary to conduct quantitative risk assessment on the debris flow in regional scale to decide the priority for the establishment of preventive measures against debris flow hazard.

In this study, quantitative risk assessment on debris flow was performed in Yongin City, Korea. Thirteen analysis areas containing 66 catchment areas which could affect the downstream properties were selected. Based on the return period of rainfall in the region, a numerical simulation was performed, and the vulnerability of each building in the studied area was estimated based on the depth and velocity of potential debris flows. The risk was then assessed in terms of direct costs at both local and regional scales.

2 BACKGROUND

The term risk has been variously defined according to researchers and research institutions. Originally, risk was derived from the Arabic word "رزق",(rizk), which means 'to seek prosperity' (Westen et al., 2012). In the middle ages, the word "risicum" was used in relation to sea trade and the legal problems of loss and damage. In English, the word risk started to be used from the 17th century (Choi et al., 2015). Risk is the combination of the probability of an event and its negative consequences (UN-ISDR), the likelihood that a specified undesired event will occur due to the realisation of a hazard by, or during work activities or by the products and services created by work activities (HSE), and the estimated impact that hazard would have on people, services, facilities, and structures in a community (FEMA, 2001).

Risk assessment includes hazard assessment, vulnerability assessment, and consequence assessment. Cui et al. (2013) conducted a risk assessment for highways damaged by debris flows in the area affected by the earthquake in 2008 Sichuan, China. They rated the risk in 5 grades through site investigation considering the vulnerability and economic value of the structure. Jakob et al. (2012) suggested four damage classes to determine building damage using an intensity index (I_{DF}) estimated by maximum flow velocity and depth of debris flow. Their method was applied to estimate total damage in Mosquito Creek, Canada for 500-year debris-flow. Jaiswal (2011) examined initiation areas of debris flow in the past and estimated temporal probability of landslide based on rainfall intensity. And then, landslide hazard and risk were assessed using landslide events that occurred between 1987 and 2007.

Existing risk assessments were conducted mostly on the areas damaged by debris flow in the past. For undamaged areas, however, it is hard to find the risk assessment considering the probability of the future event of debris flow.

Figure 1 Study area

3 STUDY AREA AND METHOD

In this study, risk assessment of debris flow was performed on Yongin, Korea (see Fig. 1). The area of Yongin City is 591.3 km^2 and the altitude is from 16.1 to 580.0 m. The population and the gross product of the area are 990,516 and 25,560 bil. KRW, respectively.

For risk assessment in regional scale, the risk framework for debris flow suggested by Choi et al. (2015) were applied and the process of the risk assessment is shown in Fig. 2.

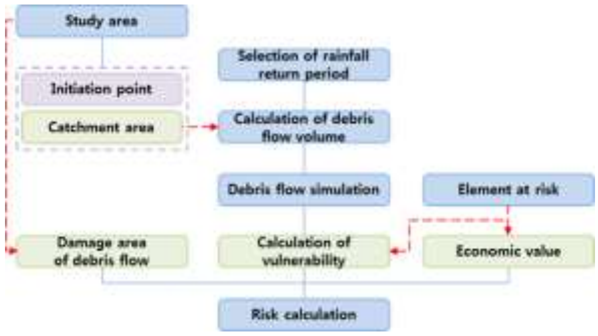


Figure 2 Regional scale risk framework of debris flow.

At first, initiation locations of debris flow and expected damage areas were determined using ArcGIS considering the topographical factors affecting debris flow occurrence. Digital elevation map in 1:5,000 scale for Yongin was used. In here, topographical factors were consisted of elevation, slope, and profile curvature (Cha, 2005; Lorente et al., 2002; Kim et al., 2008; Horton et al., 2011). Secondly, the volume of debris flow in each catchment area was calculated to simulate the expected debris flow event in accordance with the level of daily rainfall. Because rainfall is the most important factor causing debris flows, the return period was used to calculate the volume of debris flow predicted in the future. In this study, the formula for the volume of debris flow related to daily rainfall suggested by Ni et al. (2012) was used.

$$M = 7.23e^{0.0168R} \tag{1}$$

In here, M (10^4 m^3) is the volume of debris flow, R (mm) is daily rainfall. Five level of return period of rainfall (2, 10, 50, and 200 years) was considered based on the report of Ministry of Land, Transport and Maritime Affairs (2011) suggested for the same region as summarized in Table 1.

Table 1 Probability daily rainfall per return period.

Return period	*2 years*	*10 years*	*50 years*	*200 years*
Probability rainfall (mm)	160.0	272.0	370.5	451.1

Thirdly, catchment areas including initiation locations, forming concave shape, and not overlapping with others were selected. The area, then, was calibrated to estimate the volume of debris flow because the formula for the volume of debris flow by Ni et al. (2012) produced a big difference compared to the volume surveyed in Korea. Eq. (2) suggested by Chen et al. (2013) was used to calibrate the volume of debris flow.

$$V_L = 0.202 \times A_L^{1.268} \tag{2}$$

In here, V_L(m^3) is the volume of landslide, A_L(m^2) is the area of landslide. At forth, simulation of debris flow was carried out numerically at each return period of rainfall to figure out the flow depth and velocity in the course of debris flows. And finally, the vulnerability of buildings in study area was assessed considering structure types. The appraised values of buildings were surveyed and the risk was assessed based on the vulnerability and economic value of buildings.

4 SIMULATION AND RISK ASSESSMENT OF DEBRIS FLOW

The calibrated volume of debris flow according to return period is shown in Fig. 3. Estimated volume of debris flow by field investigation in 8 sites including this study area by Kang and Kim (2014) is plotted together. The result shows that the increasing catchment area and return period induces the increased volume of debris flow. Also, field investigation results are between 2 and 50 years of return period. It is the same result with the previous research on the landslide triggering rainfall in Korea by Yune et al. (2010).

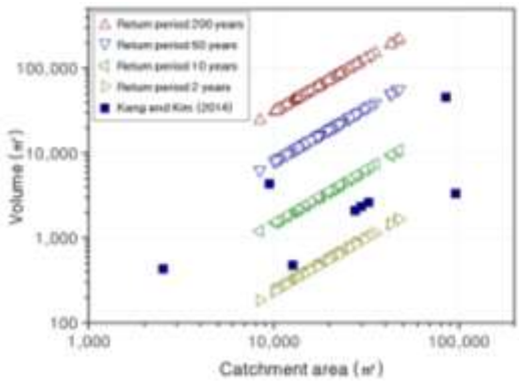


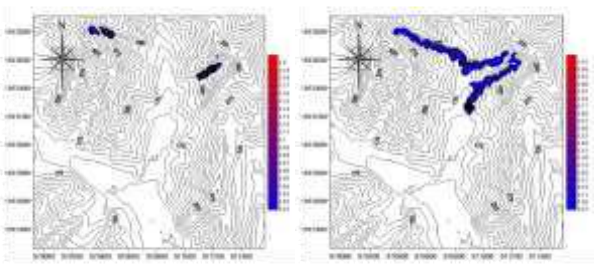
Figure 3 Volume of debris flow according to catchment areas

Among 13 study areas, 7th area was predicted to be severely damaged by debris flows because residential and industrial districts were located in the area and 2 debris flows were expected to join together and flow downstream. The area of left and right catchment in area No. 7 was 10,094 and 23,728 m^2, respectively. And the calculated volume of debris flow in each catchment was summarized in Table 2.

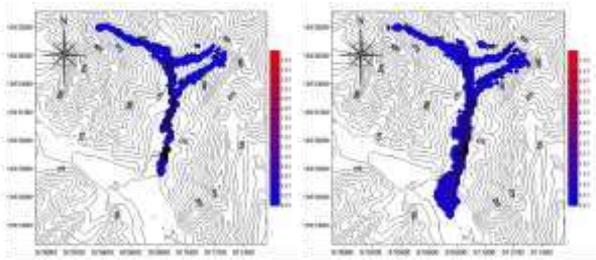
Table 2 Debris flow volume in area No. 7

Return period	*2 years*	*10 years*	*50 years*	*200 years*
Total volume in left catchment (m^3)	230	1,517	7,937	30,740
Total volume in right catchment (m^3)	683	4,484	23,459	90,862

The results of numerical simulation with the calculated volume of debris flow in area No. 7 are shown in Fig. 4. The unit of x- and y-axis in this figure is *m*.



(a) Return period: 2 years (b) Return period: 10 years



(c) Return period: 50 years (d) Return period: 200 years

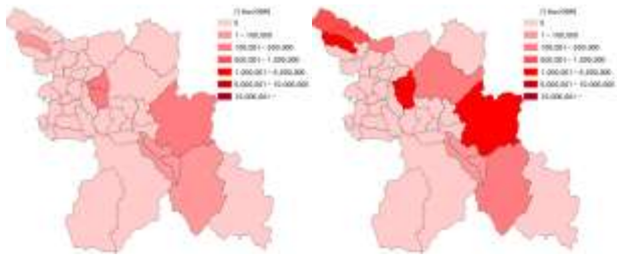
Figure 4 Debris flow simulation per return period.

For 13 study areas, the shadow angle which was defined as the ratio of vertical to horizontal travel distance of debris flow was calculated. Because most of debris flows in Korea were initiated at the elevation higher than 400 m, the results were summarized in Table 3 by 400m of elevation. In this Table, longer return period and initiation elevation below 400m resulted in gentler shadow angle. Thus, the debris flow initiated by rainfall with a longer return period at lower elevation flows further.

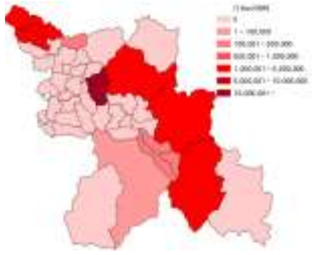
Table 3 Shadow angle of debris flow

Return period (years)	*Below 400m*	*Above 400m*	*Average*
2	18.66	21.27	19.41
10	13.50	16.56	14.37
50	9.98	12.82	10.79
200	8.39	10.85	9.09

The estimated risk for the buildings in study areas were added up by administrative district and were shown in Fig. 6. As shown in the figure, the longer return period induces higher risk especially in the central and western region. Once the risk was assessed in areas vulnerable to debris flow hazard, the area with higher risk will have a priority for the countermeasures. On the basis of this logic, the priority for the risk in 9 areas were plotted in Fig 7. Considering only population, Dongbaek-dong has the highest priority for countermeasures and Yangji-myeon and Wonsam-myeon has the 8th and 9th priority, respectively. Considering risk, however, Yangji-myeon and Wonsam-myeon has a 2nd priority in the return period of 10 years and 200 years, while Dongbaek-dong still has a first priority.



(a) Return period: 10 years (b) Return period: 50 years



(c) Return period: 200 years

Figure 6 Risk map of debris flow per return period

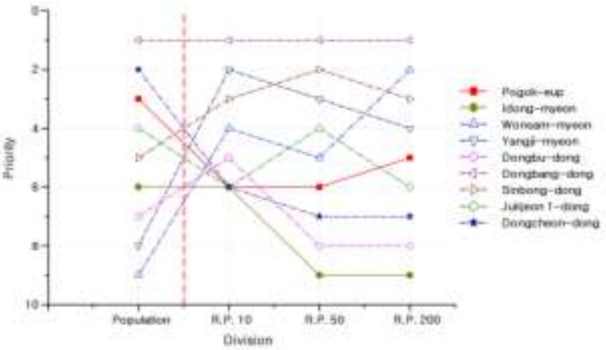


Figure 7 Risk priority of debris flow by administrative division.

As a result, a policy decision on countermeasures for debris flow in state or local government based only on population is insufficient. The quantitative risk assessment for debris flow in regional scale will be a great assistance for the effective and reasonable establishment of a preventive plan against debris flow hazard.

5 CONCLUSIONS

In this study, quantitative risk assessment for debris flow was performed on Yongin, Korea. The calculated volume of debris flow showed that the larger catchment area and longer return period of rainfall induced the larger volume of debris flow, and field investigation results were between 2 and 50 years of return period. By comparing the shadow angle of debris flows, it is shown that the debris flow initiated by rainfall with a longer return period at lower elevation flows further distance. The estimated risk for the buildings in administrative district was higher with the longer return period especially in the central and western region of Yongin City. Considering risk other than population, a priority for the countermeasures was changed significantly. Therefore, the policy decision for establishing preventive measures of debris flow needs to be conducted for the effective hazard prevention planning.

6 ACKNOWLEDGEMENTS

This research was supported by Public Welfare & Security R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (Grant No. 2012M3A2A1050979) and by Disaster Prevention Institute of Gangneung-Wonju National University.

7 REFERENCES

Cha, K.S., Chang, P.W., Woo, C.W., and Kim, S.P. 2005. Prediction of potential landslide sites using deterministic model. *Journal of the Korean Society of Agricultural Engineers* 47 (6), 37-45.

Chen, Y.C., Chang, K.T., Chiu, Y.J., Lau, S.M., and Lee, H.Y. 2013. Quantifying Rainfall Controls on Catchment-Scale Landslide Erosion in Taiwan. *EARTH SURFACE PROCESSES AND LANDFORMS* 38. 372-382.

Choi, G.M., Lee, S.W., and Yune, C.Y. 2015. Risk assessment of 2011 debris flow hazard area in Yongin city. *Journal of Korean Society Hazard Mitigation* 15 (2), 165-178.

Ciurean, R., Chen, L., Hussin, H., Van Westen, C.J., Glade, T., Frigerio, S., and Pasuto, A. 2014. Quantitative vulnerability assessment of buildings to debris-flows in Fella River Basin using run-out modeling and damage data from the 29th of August 2003 event. *International Conference, Analysis and Management of Changing Risks for Natural Hazards*, 1-9.

Cui, P., Xiang, L.Z., and Zou, Q. 2013. Risk Assessment of Highways Affected by Debris Flows in Wenchuan Earthquake Area. *Journal of Mt. Science* 10, 173-189.

Federal Emergency Management Agency 2001. Understanding Your Risks.

Ghosh, S., Van Westen, C.J., Carranza, E.J.M., and Jetten, V.G. 2012. Intergrating spatial, temporal, and magnitude probabilities for medium-scale landslide risk analysis in Darjeeling Himalayas, India. *Landslides* 9, 371-384.

Haugen, E.D. and Kaynia, A.M. 2008. Vulnerability of Structures Impacted by Debris Flow. *10th International Symposium on Landslides and Engineered Slopes, Xian, China*, 381-387.

Horton, P., Jaboyedoff, M., Zimmermann, M., Mazotti, B., and Longchamp, C. 2011. Flow-R, a model for debris flow susceptibility mapping at a regional scale - some case studies. *5th International Conference on Debris-Flow Hazards Mitigation, Padua, Italy, Italian Journal of Engineering Geology and Environment*, 875-884.

Health and Safety Executive, http://www.hse.gov.uk

Jaiswal, P. 2011. Landslide risk quantification along transportation corridors cased on historical information. *Ph.D. Dissertation, University of Twente.*

Jakob, M., Stein, D., and Ulmi, M. 2012. Vulnerability of Buildings to Debris Flow Impact. *Natural Hazards* 60, 241-261.

Kang, H.S., and Kim, Y.T. 2014. Physical vulnerability function of buildings impacted by debris flow. *Journal of Korean Society Hazard Mitigation* 14 (5), 133-143.

Kim, G.S. 2008. Model of road design and location of urban facilities for the prevention of disasters. *Journal of Korean Society Hazard Mitigation* 8 (3), 59-65.

Lorente, A., Garcia-Ruiz, J.M. Begueria, S., and Arnáez, J. 2002. Factors explaining the spatial distribution of hillslope debris flows. *Mountain Research and Development* 22, 32-39.

Melelli, L. and Taramelli, A. 2004. An example of debris-flows hazard modeling using GIS. *Natural Hazards and Earth System Sciences* 4, 347-358.

Ministry of Land, Transport and Maritime Affairs 2011. A study of improvement and supplement of probability rainfall.

Ni, H.Y., Zheng, W.M., Tie, Y.B., Su, P.C., Tang, Y.Q., Xu, R.G., Wang, D.W., and Chen, X.Y. 2012. Formation and Characteristics of Post-Earthquake Debris Flow: A Case Study from Wenjia Gully in Mianzhu, Sichuan, SW China. *Natural Hazards* 61, 317-335.

Onnara Real Estate Information Portal, http://www.onnara.go.kr

Simoni, A. Mammoliti, M. and Berti, M. 2011. Uncertainty of debris flow mobility relationships and its influence on the prediction of inundated areas. *Geomorphology* 132, 249-259.

UN-ISDR, http://www.unisdr.org/we/inform/terminology

Yune, C.Y., Chae, Y.K., Paik, J.C., Kim, G.H., and Lee, S.W. 2013. Debris Flow in Metropolitan Area - 2011 Seoul Debris Flow. *Journal of Mountain Science* 10 (2), 199-206.

Yune, C.Y., Jun, K.J., Kim, K.S., Kim, G.H. and Lee, S.W. 2010. Analysis of Slope Hazard-Triggering Rainfall Characteristics in Gangwon Province by Database Construction. *Journal of the Korean Geotechnical Society* 26(10), 27-38.

Westen, C.J.V., Alkema, D., Damen, M.C.J., Kerle, N., and Kingma, N.C. 2011. Multi-Hazard Risk Assessment: Guide Book. *UNU-ITC DGIM*, Netherlands.