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Quantitative Debris Flow-Induced Vulnerability Assessment

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Abstract: Debris flows are rapid and destructive mass movements that pose severe threats to infrastructure and human settlements in mountainous regions. Although hazard intensity and spatial susceptibility have been widely investigated in previous studies, quantitative assessments of physical vulnerability remain comparatively underexplored. In this study, a quantitative analysis for building vulnerability to debris flow impacts was developed, with explicit consideration of building types. Two broad categories were assessed: reinforced concrete (RC) frame structures and non-RC frame structures, including wood, lightweight steel, and unreinforced brick masonry. The analysis demonstrates that non-RC frame structures exhibit markedly higher susceptibility to debris flow impacts, frequently resulting in severe structural damage or complete collapse. Conversely, RC frame structures display considerably greater resistance, with outcomes generally limited to minor damage or no structural impairment. The NVI comparison (53.9 observed vs. 66.3 predicted) demonstrates generally consistent results, with the model exhibiting a slight conservative bias. This reliability strengthens its usefulness for risk assessment, disaster mitigation, and resilient land-use planning in debris flow-prone regions.

Keywords: ***Building vulnerability, Building types, Quantitative assessments, Debris flows.***

Introduction

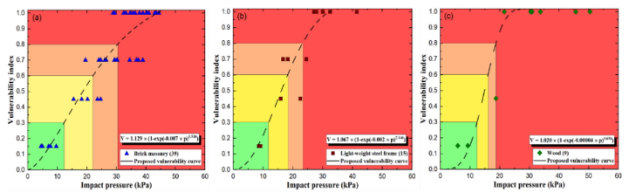
Debris flows are among the most hazardous mass movements in mountainous environments, characterized by rapid downslope movement of saturated soil, rock, and organic material (Santi et al., 2011, Song et al., 2025). Their high velocity and impact forces often lead to severe consequences, including damage to infrastructure, disruption of transportation networks, and loss of human lives (Nguyen et al., 2025). With increasing frequency and intensity of extreme rainfall events under climate change, debris flow hazards are expected to become more prevalent, underscoring the urgent need for comprehensive risk assessments.

Conventional approaches to debris flow risk analysis largely focused on hazard intensity, spatial susceptibility, and exposure of elements at risk. While these factors provide valuable insights into potential disaster scenarios, the dimension of physical vulnerability, particularly the structural response of buildings to debris flow impacts, has received comparatively limited attention. Vulnerability is not uniform across the built environment; rather, it is strongly influenced by structural characteristics such as construction material, design standards, and load-bearing capacity. Neglecting this variability may result in underestimation or misrepresentation of disaster risk.

In this study, we developed a quantitative analysis for debris flow-induced vulnerability assessment that explicitly accounts for differences among building types. Two principal categories are considered: reinforced concrete (RC) frame structures and non-RC frame structures, including wood, lightweight steel, and unreinforced brick masonry. By integrating structural fragility analysis with debris flow impact scenarios, this analysis aims to provide a more realistic evaluation of potential damage.

Proposed physical vulnerability curve

Figure 1 shows the physical vulnerability curves for non-RC frame structures. These curves were developed from 22 debris flow events with a total of 87 damaged buildings (Lee et al., 2024). The maximum impact pressure considered for each structural type is 43.9 kPa for brick masonry, 32.0 kPa for lightweight steel frames, and 24.3 kPa for wood. Beyond these thresholds, the vulnerability index is assumed to reach 1, indicating complete failure. Up to a vulnerability index of 0.3, all three curves exhibit similar behavior. However, once the vulnerability index exceeds 0.3, the proposed vulnerability curves for unreinforced brick masonry, lightweight steel frame, and wood structures diverge markedly, reflecting significant differences in structural response to increasing debris flow impact pressures.



(a) Brick masonry (b) Light-weight steel frame (c) Wood

Figure 1, Physical vulnerability curves for non-RC frame structures.

Figure 2 presents a comparison of physical vulnerability curves for different building types under increasing debris flow impact pressure. Reinforced concrete, reinforced masonry, and reinforced moment structures show relatively low vulnerability, with gradual increases even at higher pressures. In contrast, unexhibited types, particularly wood, light-steel, and brick masonry, exhibit steep rises in vulnerability at much lower impact pressures, reaching near-total failure quickly. These curves highlight the strong influence of structural types on debris flow-induced damage potential.

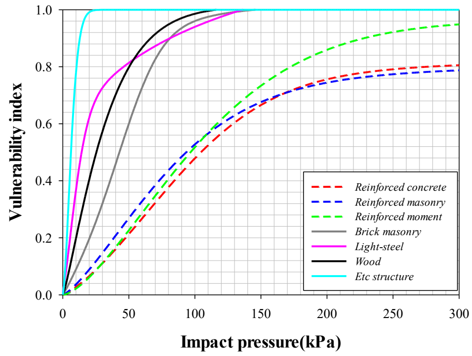


Figure 2, Comparation of physical vulnerability curves.

Quantitative vulnerability assessment

In this study, a debris flow event in Yecheon County, Korea, was analyzed to assess the physical vulnerability of different building types. Figure 3 presents the distribution of buildings by structural type within the study area.

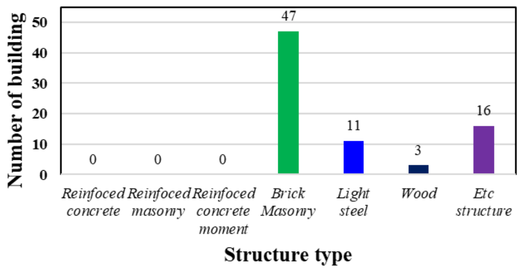


Figure 3, Building type in the study area.

Figure 4 illustrates the outcomes of the physical vulnerability assessment across different structural types. The comparison demonstrates that the proposed vulnerability curves provide a reliable representation of building performance, accurately capturing the observed vulnerability.

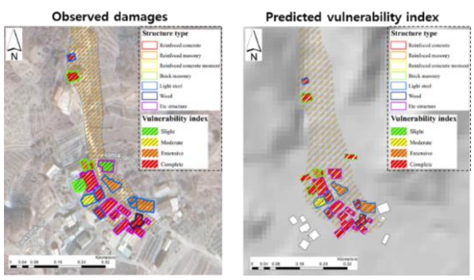


Figure 4, Result of vulnerability assessment.

Table 1 compares observed damages with predicted vulnerability indices across different damage levels. The results indicate that while the model generally captures the distribution of damage, slight damage is underestimated, and complete damage is slightly overestimated. The calculated NVI values are 53.9 for observed data and 66.3 for predictions, suggesting that the proposed model tends to predict higher overall vulnerability.

Table 1, Normalize vulnerability index (NVI).

Damage level	Observed damages	Predicted vulnerability index
None	10	8
Slight	2	0
Moderate	1	1
Extensive	4	4
Complete	12	16
NVI	53.9	66.3

Conclusion

The proposed model reliably estimates debris flow vulnerability across different building types, with non-RC structures showing higher susceptibility than RC frames. While slight damage was underestimated and complete damage slightly overestimated, the NVI comparison (53.9 observed vs. 66.3 predicted) indicates generally consistent results, providing a conservative basis for risk management and mitigation planning.

Acknowledgement

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