Quantitative Rockfall Damage and Risk Analysis on Railroad Infrastructure after the 2024 Hualien Earthquake

Cheng-Han Lin[1*], Chin-Hao Kuo[2], Yu-Chao Lin[2], Chun-Hua Chen[2] and Meng-Chia Weng[1]

[1]Department of Civil Engineering, National Yang Ming Chia Tung University, Hsinchu, Taiwan
[2]Department of Railway Engineering, CECI Engineering Consultants, Inc., Taipei, Taiwan

(*Corresponding E-mail: chenghan.stephan.lin@proton.me)

Abstract: Taiwan has abundant mountains and limited plains, resulting in transportation networks often constructed along valleys and riverbanks. Particularly for critical transportation infrastructure like the Eastern Taiwan North-Link Railway Line, segments remain susceptible to significant rockfall hazards. On April 3, 2024, a Mw 7.1 earthquake struck Hualien, Taiwan, triggering widespread coseismic rockfalls that damaged the North-Link Railway Line. Taking the mileage of K51 of the North-Link Railway Line as the case study, this study established a rockfall database using iPhone light detection and ranging (LiDAR) during the disaster reconnaissance. A quantitative rockfall damage and risk analysis based on three-dimensional rockfall simulations was then performed to contribute to effective mitigation strategies for railroad infrastructure in terms of rockfalls.

Keywords: ***Rockfall, Damage and risk analysis, Railroad infrastructure, Three-dimensional simulation.***

Introduction

The 2024/04/03 Hualien Earthquake was the third major earthquake in eastern Taiwan since 2018 and 2022. Compared to the previous two earthquakes, the 2024/04/03 Hualien Earthquake was unique because it triggered widespread coseismic landslides, which were mostly identified as rockfalls (Chang et al., 2024). As shown in Figure 1, the coseismic rockfalls heavily damaged the Eastern Taiwan North-Link Railway Line, and the post-earthquake hazard chains posed significant challenges to subsequent reconstruction efforts. The research team immediately conducted disaster reconnaissance at the K51 site on April 3, 2024 (Figure 1 a). We adopted iPhone LiDAR technique to model the rock fragments that damaged the railway infrastructures for building a rockfall database (Figure 2 a). The database shows that the lithology of the rock fragments is marble, and the block geometry is sub-equant to equant (Figure 2 b). The volume of each fragment ranges from 0.07 m^3 to 17 m^3. Combined with the previous rockfall event record, the rockfall frequency-magnitude relationship for the K5 site was established and used to estimate rockfall and block volume scenarios in the damage and risk analysis (Figure 2 c). In this study, we show the results of a midterm rockfall risk scenario, corresponding to maximum possible volumes of 14 m^3 with a 15-year return period, to illustrate how the numerical simulations can aid the formulation of the mitigation strategies.

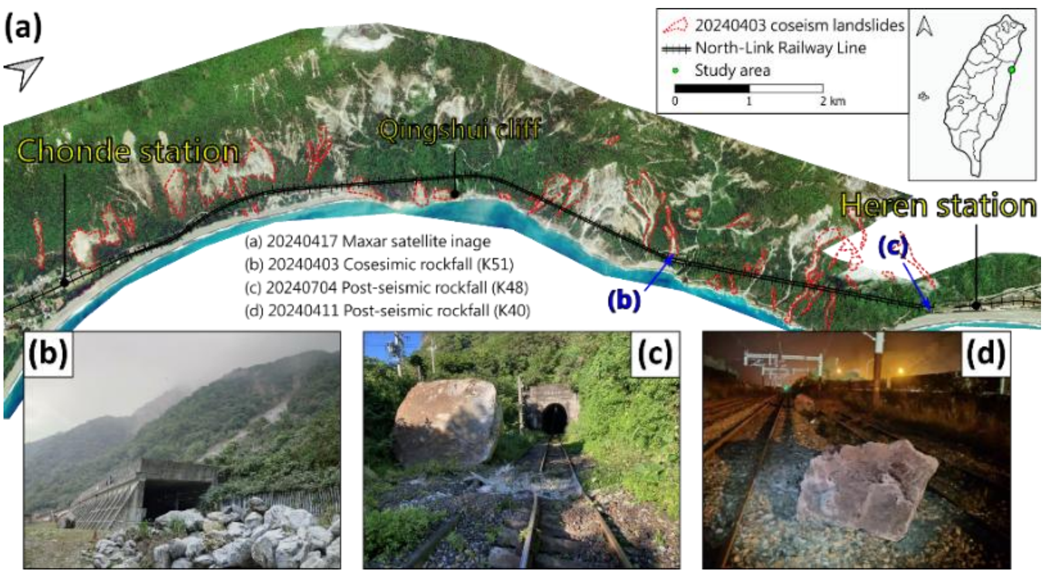

Figure 1, (a) Coseismic landslides triggered by the 20240403 Hualien Earthquake. Photos of the (b) coseismic rockfall at mileage of K51 and (c)(d) post-seismic rockfall of the earthquake hazard chains at K40 and K48 within 3 months.

Results and Discussions

The rockfall simulations were performed using the RAMMS: Rockfall process-based model (Leine et al., 2014). The terrain and forest parameters were first calibrated from the 20240403 rockfall database and then applied to scenario modeling (Table 1). The simulation of the midterm rockfall risk scenario provides quantitative information related to rockfall damage and mitigation design, including jump height (*H*), kinematic energy (*K*), and rockfall count. As shown in Figure 3 a, the information was used to define rockfall hazard conditions, called "rockfall hazard vector (*RHV*)", proposed by Crosta and Agliardi (2003). This study determined the classes of jump height and kinematic energy as $0 < H \leq 3$ m, $3 < H \leq 8$ m, > 8 m, and $0 < k \leq 300$ kJ, $300 < k \leq 4000$ kJ, > 4000 kJ.

We observed that the western track at the K51 site is more prone to rockfall damage under the midterm rockfall risk scenario than the eastern track (Figure 3 a). The distribution of the *RHV* classification is also consistent with the documented rockfall event locations along the railway and highway. Because the western track already has a 130-m-long rock shed built in 2018, the mitigation strategy was considered to extend the rock shed to the whole track. In addition, the performance of the existing rock shed should be examined under the given rockfall risk scenario. As shown in Figure 3 b, the designed capacity of the rock shed can mitigate the rockfall hazard scenario for the extended section from K51+200 to K51+300 in terms of jump height and kinematic energy. However, for the existing section, the performance of the rock shed below the potential rockfall damage, especially regarding the jump height. The results indicate that the rock block will jump over the existing rock shed and damage the eastern track. In addition, most parts of the rock shed could break due to the insufficient design energy capacity.

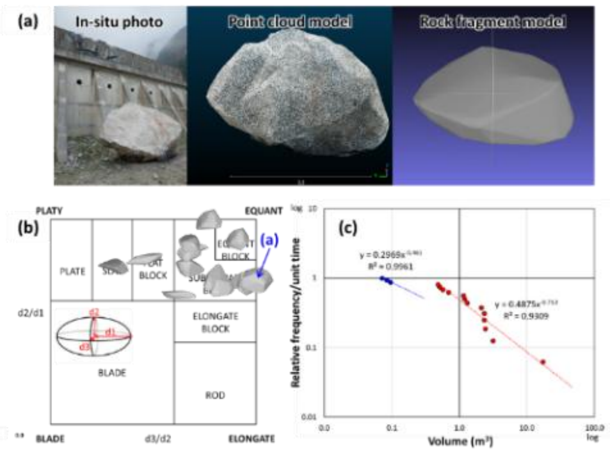

Figure 2, (a) In-situ rock blocks modeled by iPhone LiDAR technique; (b) Geometry of rock fragments that damaged the railroad infrastructures on 2024/04/03 coseismic rockfall at the K51 site; (c) Block frequency-volume relationship within 9 years.

Table 1, Terrain and forest parameters used in this study

Terrain		M_E	C_d
Bareland and Erosion gully		3.0	2.3
Vegetations		3.0	1.5
Artificial structures		75.0	2.0
Forest	**Density (Tree/ha)**	**Diameter at breast height**	
		μ	**σ**
Medium Forest	400	28	7

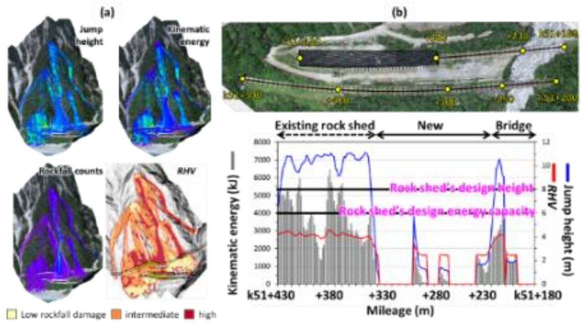

Figure 3, (a) Results of rockfall simulations and rockfall hazard vector (RHV); (b) Rock shed design effectiveness plot along the western track at the K51 site based on the damage and risk analysis.

Concluding remarks

This study addressed the rockfall hazard assessment for the railroad infrastructures based on the quantitative rockfall damage and risk analysis. Taking the K51 of the North-Link Line as the case study, we determined the effectiveness of the existing and new design of the rock shed under the 15-year return period of the rockfall risk scenario. To address the shed's low capacity, additional barriers should be installed above the railway to reduce rockfall impact. The new design can be re-evaluated using the proposed workflow, which has proven effective for other post-seismic rockfalls in railway reconstruction.

References

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