System of highway slope disaster information collection, integration, simulation and judgement

Chia-Chi Chiu
National Taipei University of Technology, Taipei, Taiwan

Wen-Jie Shiu
Sinotech Engineering Consultants Inc., Taipei, Taiwan

Ching-Fang Lee
Sinotech Engineering Consultants Inc., Taipei, Taiwan

Meng-Chia Weng
National Yang Ming Chiao Tung University, Hsinchu, Taiwan

Che-Ming Yang
National United University, Miaoli, Taiwan

ABSTRACT: Landslide and rockfall disasters frequently occur on road systems. Therefore, analyzing the disaster rapidly and deciding on the remediation method, is the key to reducing the loss. We have developed a 'Highway slope disaster information collection, integration, simulation and judgment system' which has three parts: (1) Geohazard rapid report system; (2) Multidisciplinary geological survey; and (3) Site-specific landslide simulation. This paper focuses on theYusui Stream debris flow and the disaster of the Minbaklu bridge as case studies to demonstrate the application of the aforementioned three components in disaster assessment. The key factor such as geological, terrain, distribution of weak plane, volume, process, and landslide mechanism, and finally provide a disaster report to concerned units for the assistance in follow-up decisions.

Keywords: Slope, Disaster investigation, Information integration, Numerical simulation, Geological investigation.

1 INTRODUCTION

Mountains comprise around 70% of Taiwan, necessitating that roads and railways have to follow the terrain of the mountains and rivers. However, Taiwan is situated in a plate boundary zone and a monsoon climate zone, which can lead to immature geology and extreme weather conditions. As a result, road slope disasters occur, damaging the transportation system. However, as transportation should not be interrupted, it is crucial to urgently address the research tasks of quickly detect road slope disasters, planning effective investigation operations, analyzing the triggering factors, providing rescue strategies, and suggesting remediation engineering designs.

Therefore, we developed a highway slope disaster analysis procedure with up-to-date technologies called "GeoPORT", which is a combination of the words "Geohazards" and "Report". The program integrates many new technologies for slope disaster analysis, including a geohazard early warning system, multi-scale geological surveys, and full-scale numerical simulations, and has practiced the investigation procedure on several cases. When a highway or road slope disaster occurs, we will immediately integrate high-precision topographical, geological, mechanical, and hydrological data and other information to quickly collect post-disaster information such as topography, landslide volume, influenced area, triggering factors, etc. Further, the information will be used to analyze the collapse mechanism to suggest subsequent engineering remediation.

2 FRAMEWORK

The operation of GeoPORT is shown in Figure 1 (Modified based on Weng et al. 2021). This system can be divided into three parts: geohazard rapid report system, multidisciplinary geological survey and site-specific landslide simulation.

2.1 Geohazard rapid report system

Previous research has shown that high-sensitivity broadband seismographs are capable of recording the surface vibration signals generated when landslides occur. High-resolution waveform signals will help understand the landslide mechanism and characteristics of collapse events. The collapse occurrence location can be inferred by utilizing the time difference between the waveform signals caused by the collapse, which are received by different stations.; through time-frequency analysis results, the change in waveform frequency can be known, and the collapse occurrence process can be estimated (because low-frequency waves represent larger bodies, high-frequency waves represent more dispersed bodies).

2.2 Multidisciplinary geological survey

The multidisciplinary geological survey is a method of assessing the geological conditions of disaster areas through surveys of various scales. It comprises of three scales: remote, medium, and close. The remote-scale investigation uses remote sensing images and regional survey maps to analyze background information of disaster; the medium-scale is to obtain the surface characteristics of the disaster area through unmanned aerial photography; and the close-scale is to conduct field surveys manually. Geological survey methods of different scales have their own specific objectives.

2.3 Site-specific landslide simulation

Numerical analysis can reproduce, analyze and predict hazards, enabling subsequent engineering management to assess the suitability of remediation methods. RAMMS, 3DEC, and PFC are the primary analysis tools in our system. RAMMS simulates natural disasters such as landslides, rockfalls, and debris flows. 3DEC simulates the rock material as a combination of discrete polyhedrons and analyzes the force response through the contact status between polyhedrons. It is particularly suitable for simulating rock slope hazards controlled by joint surfaces. PFC simulates the behavior of geological materials by modeling particles and their interactions; it is ideal for analyzing rockfall trajectory and debris flow. PFC can also visualize bond failure behavior; its circular particles have high fluidity.

Regardless of whether it's RAMMS, 3DEC, or PFC, the modeling process requires geological information related to spatial geometry, such as: pre-disaster topography, post-disaster topography, the orientation of joints, and collapse area. The information can be obtained through a multidisciplinary geological survey with the aid of high-precision DEMs produced from airborne lidar surveying for pre-disaster topography, DSM produced by unmanned aerial vehicles for post-disaster topography, the orientation of joint planes obtained by extracting point cloud features, and collapse area identified by experts on unmanned aerial vehicle imagery. Material parameters required for simulation can be obtained from past engineering data, and rough estimates can also be made during field surveys using simple on-site tests (such as Schmidt hammer testing) and rock mass rating methods. Once the analysis is completed, the simulation results can be verified using checkpoints such as the accumulation of collapsed material, the process and appearance of collapse (if there is a video record of the failure), and the extent of collapse impact. The seismic wave analysis results can also be used as checkpoints for the simulation because they can identify the timing of changes in collapse history and block movement behavior.

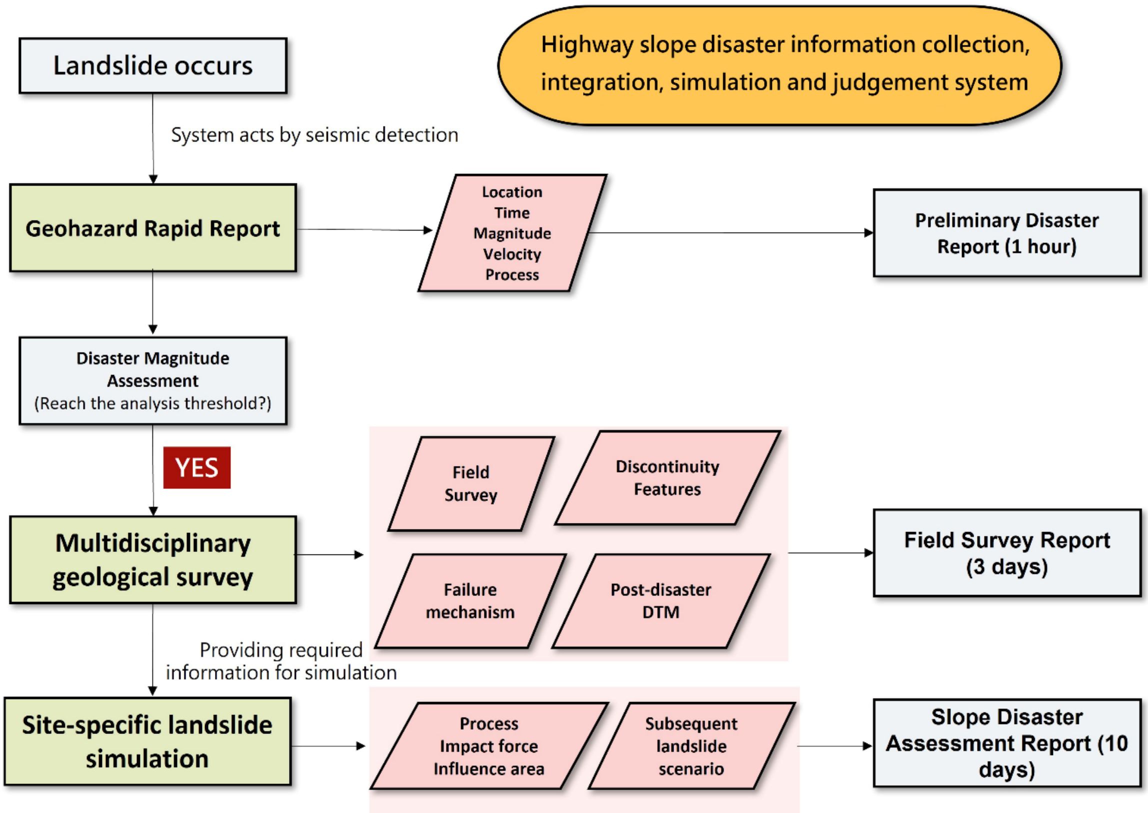


Figure 1. The framework of Highway slope disaster information collection, integration, simulation and judgment system. (Modified based on Weng et al. 2021).

3 APPLICATION

On August 7, 2021, Typhoon Lupit invaded Taiwan, and the Minbaklu Bridge at the confluence of the Yusui River and Laonong River was severely damaged by a debris flow, resulting in the bridge deck being washed away and isolating nearly 400 upstream residents for 19 days (Figure 2a-b). The material of the debris flow comes from upstream of the Yusui Stream. However, the Yusui Stream is at least 7 km long (Figure 2c), and it is difficult to perform traditional field survey methods to find the landslide's birthplace. Therefore, we used microseismic signals to locate the source and analyze the changes in its collapse history (Figure 3). The analysis results show that the source mainly comes from Silabaku Mountain (Figure 2d) at the uppermost start of Yusui Stream; the collapse occurred at 9:16:52 am with a duration of ~ 86 s.

The landslide occurred in a remote mountainous area with no convenient road access. Therefore, we used unmanned aerial vehicles to obtain post-disaster topographical features. Figure 4 shows the elevation changes of pre-disaster topography and post-disaster topography. It can be found that there is a natural dam about 70m high at CC', and the middle section of the watershed is mostly riverbed erosion and deposition in the form of an alluvial fan.

To comprehend the overall process of the disaster, two distinct types of software were employed for simulation in this study. Because debris flow is more fluid-like, RAMMS software was used for debris flow analysis. The damage to the Minbaklu Bridge is a debris flow - structures interaction phenomenon. Therefore, PFC was used for reenactment. Figure 5 shows the debris flow simulation result; this simulation uses an eroded bed simulation mode, meaning the riverbed will be eroded. The simulation results show that the erosion depth in the middle section of the watershed is more profound, the amount of soil and sand in the landslide increased by 11%, and the total volume is about 1.76x107 m3. The alluvial fan of the landslide is fan-shaped, and the slope angle is about 6.1 degrees.

Figure 6 is the model and process of reenacting the Minbaklu Bridge collapse using PFC. Figure 6b-g shows the process of the Minbaklu Bridge being destroyed. Initially, the debris flow did not significantly impact the bridge but gradually accumulated in front of the bridge piers. When the accumulation of debris height is close to the bridge deck, the materials under the bridge deck begin to rise, reducing the normal force and friction resistance between the bridge deck and the bridge piers (Figure 6d). When the bridge deck is pushed by force greater than the resistance force, the bridge deck begins to displace. Finally, the bridge deck is pushed away from its original position, causing damage to the bridge. Comparing the actual scene of the collapsed bridge, it can be found that the two forms of damage are pretty consistent, which proves that numerical simulation can be used as a tool for reenactment and prediction of disasters.

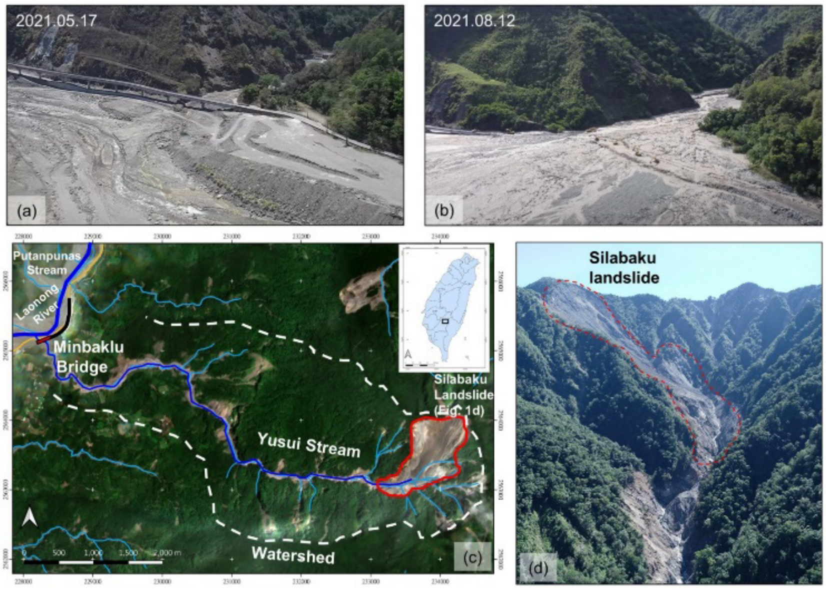


Figure 2. Yusui Stream debris flow and Minbaklu Bridge failure.

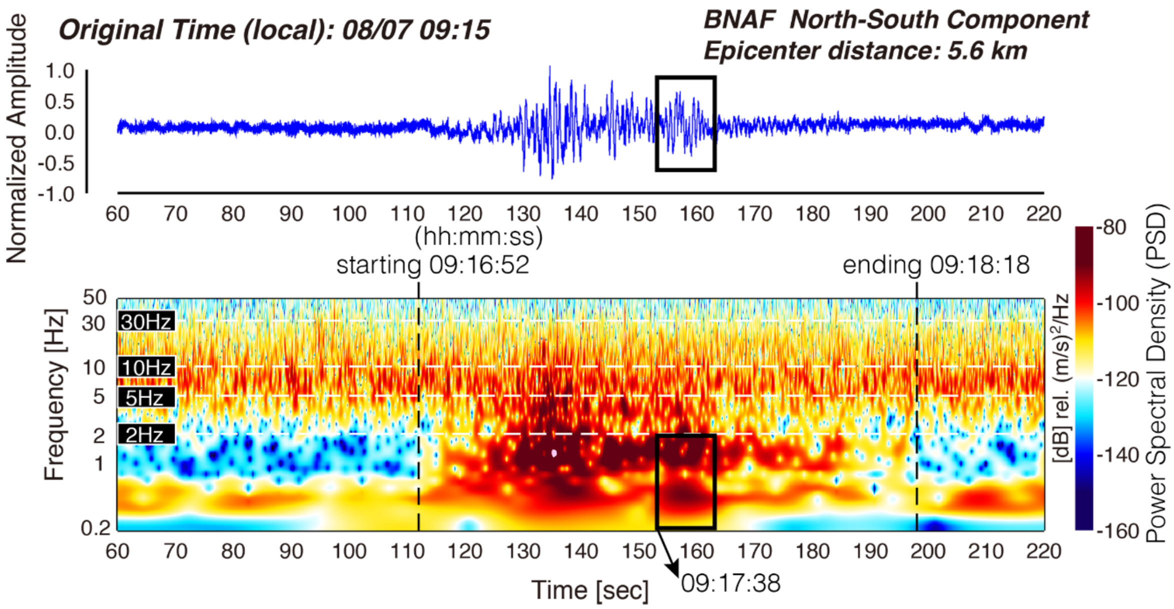


Figure 3. Results of microseismic analysis.

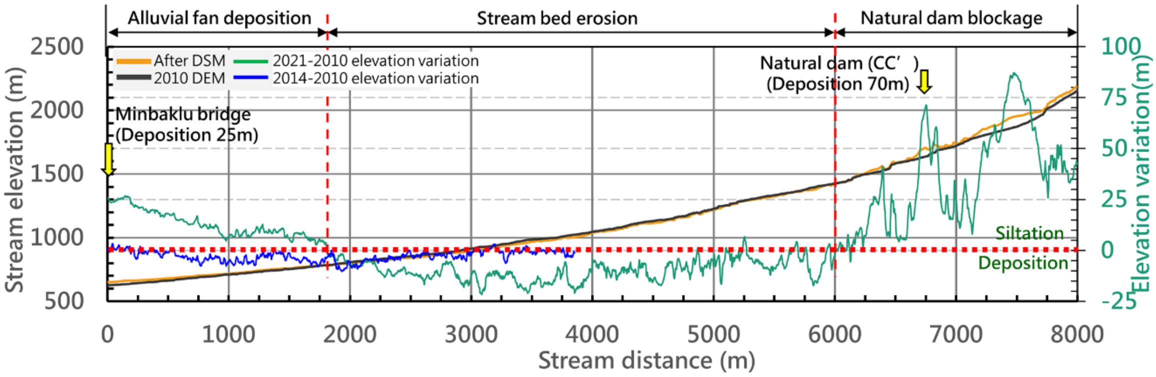
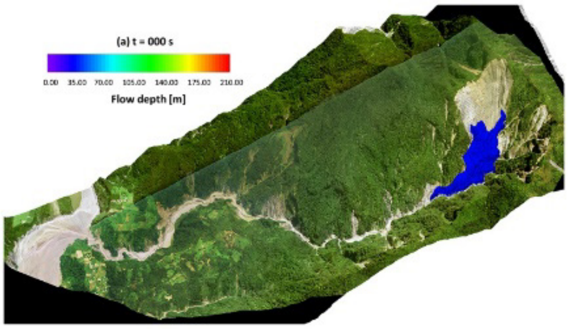
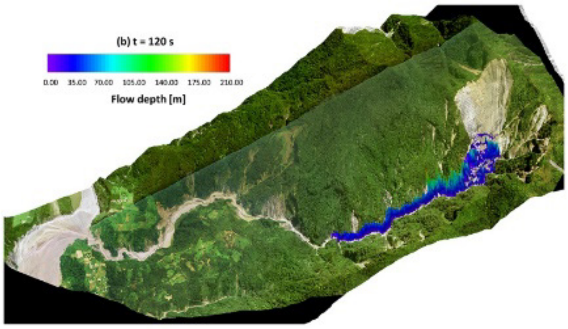


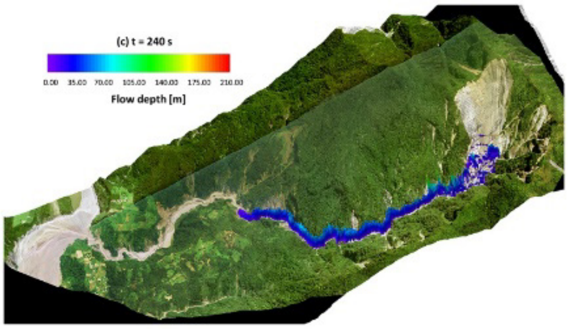
Figure 4. Landslide erosion and deposition.



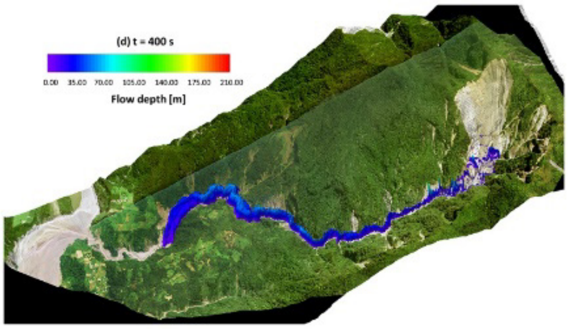
(a) t=0 s



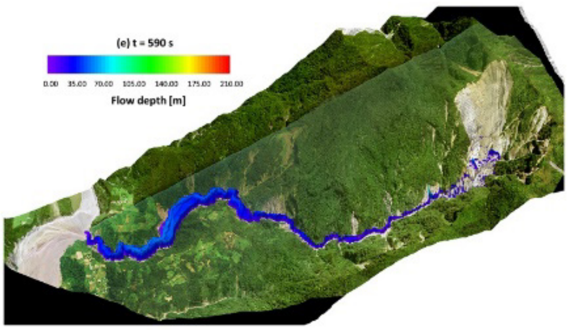
(b) t=120 s



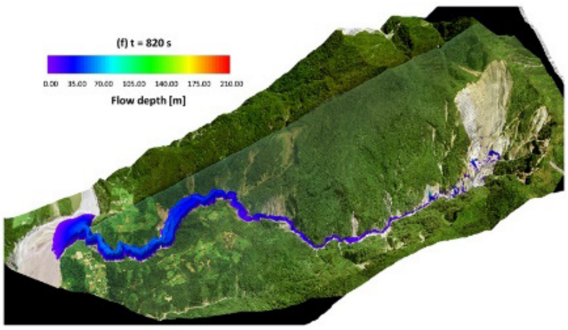
(c) t=240 s



(d) t=400 s



(e) t=590 s



(f) t=820 s

Figure 5. Debris flow simulation by RAMMS.

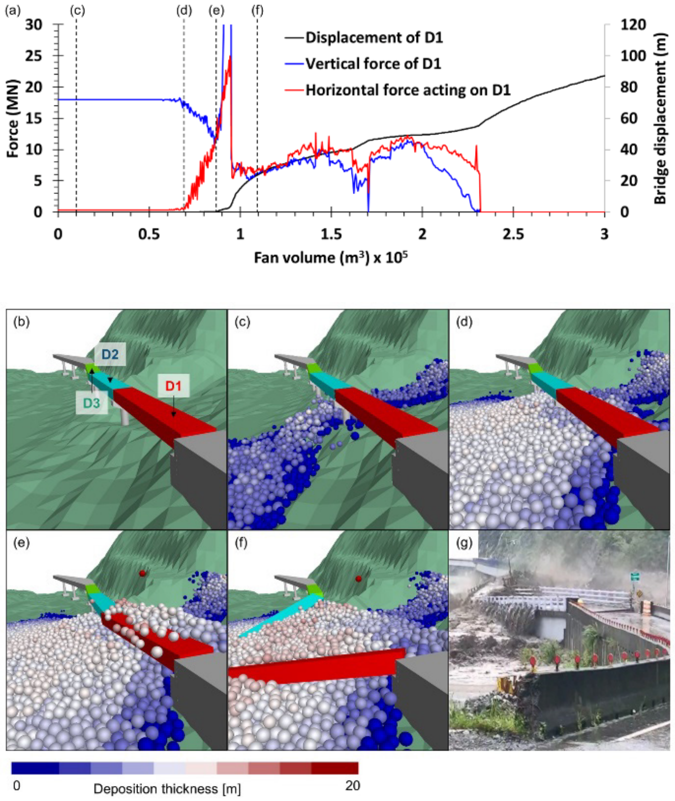


Figure 6. PFC simulation of the failure process of the Minbaklu Bridge.

4 CONCLUSION

Future trends involve the integration of various new technologies to assist in the investigation of slope disasters. Seismic wave analysis can infer the occurrence and process of the disaster; Unmanned aerial vehicle photogrammetry is a flexible method that can perform an immediate field investigation; Numerical simulations can be utilized to recreate the disaster process and predict possible failures. The implementation of these techniques can assist in elucidating road slope disaster mechanisms and enhance the efficiency of disaster relief decision-making. However, it should be emphasized that the application of these technologies does not mean that traditional geological exploration is unimportant. On the contrary, these techniques and conventional geological surveys can complement each other. The methods proposed in this study prioritize inferring disaster mechanisms to enable quick response for relief efforts. Simultaneously, geological exploration is utilized to identify the actual causes of disasters and develop long-term management plans.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Science and Technology, Taiwan, for financially supporting this research under Contracts MOST 109-2124-M-027-001, MOST 110-2124-M-027-001 and MOST 111-2124-M-027-001.

REFERENCES

Weng, M.C., Lin C.H., Shiu, W.J., Chao, W.A., Chiu, C.C., Lee, C.F., Huang, W.K., & Yang, C.M. 2022. Towards a rapid assessment of highway slope disasters by using multidisciplinary techniques. Landslides 19, pp. 687-701. DOI: 10.1007/s10346-021-01808-0