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Rehabilitation of Southern Cross-Island Highway in a complex disaster environment

Réhabilitation de la route transversale du sud de Taïwan dans un environnement soumis à des processus catastrophiques complexes

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ABSTRACT: In 2009, Typhoon Morakot struck southern Taiwan and caused severe damages especially to Southern Cross-Island Highway between Qinhe and Fuxing villages. The typhoon not only accumulated 2,500 mm of rainfall, but also caused sedimentation of more than 30m within a short time. Along the Laonong River, the 12 km long roads and bridges were covered by the riverbed. The unstable hydrological and geological conditions of this area have resulted in a high potential of sedimentation, making it difficult to select a route to rehabilitate the highway. Consequently, a series of safety assessment was carried out before initiating the project; and then, before the surrounding environment reached long-term stability, a 10-to-15-year-long mid-term construction program was launched. The selection of rehabilitation route, on the other hand, has taken compound disasters, including floods, landslides, aggradation and debris flow, into consideration. During the assessments, multi-temporal satellite image analysis, LiDAR derived DEM, ground survey and fieldwork were used to, through various investigation methods, identify geomorphic changes of the region and select the rehabilitation route. The mid-term construction program was completed in 2017, successfully bringing new hopes to Southern Cross-Island Highway.

Résumé : En 2009, le typhon Morakot a frappé le sud de Taïwan et causé de graves dommages, en particulier à la route transversale du sud de Taïwan entre Qinhe et Fuxing. Durant le typhon, les précipitations ont atteint 2’500 mm, et plus de 30 m de sédiments se sont accumulés en peu de temps par endroits. Les routes et ponts qui longent la rivière Laonong sur plus de 12 km étaient inondés. Les conditions hydrologiques et géologiques instables de cette zone ont abouti à un fort potentiel de sédimentation, rendant difficile le choix d'un itinéraire pour réhabiliter l'autoroute. Par conséquent, une série d'évaluations de sécurité a été réalisée avant de lancer le projet et, avant que le milieu environnant n'atteigne une stabilité à long terme, un programme de construction à moyen terme de 10 à 15 ans a été lancé. De plus, le choix de l'itinéraire de réhabilitation a pris en considération la nature complexe des processus catastrophiques impliqués, y compris les inondations, les glissements de terrain, le dépôt de sédiments et les coulées de débris. Au cours des évaluations, l'analyse des images satellitaires multitemporelles, le MNT dérivé du LiDAR, les relevés au sol et les travaux sur le terrain ont été utilisés pour identifier les changements géomorphologiques de la région et sélectionner l'itinéraire de réhabilitation avec diverses méthodes d’investigation. Le programme de construction à moyen terme s'est achevé en 2017, apportant avec succès de nouveaux espoirs à la route transversale du sud de Taïwan.

KEYWORDS: typhoon Morakot; river deposition; complex disaster; rehabilitation.

1 INTRODUCTION

In 2009, Typhoon Morakot destroyed Southern Cross-Island Highway in Taiwan. The section between Qinhe and Fuxing village was damaged severely. The storm produced 2,578mm of rainfall and caused river deposition of more than 30m in a short period of time (see Figure 1).

The reconnaissance by Chen and Wu (2009) showed that the severe slope failure and debris flows of Laonoan basin were related to the huge rain accumulation and long duration of intense precipitation by the typhoon Morakot.

Along the Laonong River, there were 12 kilometers of roads and bridges covered under the riverbed. Due to the unstable hydrology and geology conditions of this area, it possesses high potential for river deposition making it difficult to choose a highway rehabilitation route.

2 PURPOSE

After Typhoon Morakot, the slope stability around this site was undermined and the overall environment turned unsteady. The drastic river deposition and the frequent debris flow made temporary road repairs unsustainable, leading to multiple repair failures (see Figure 2).

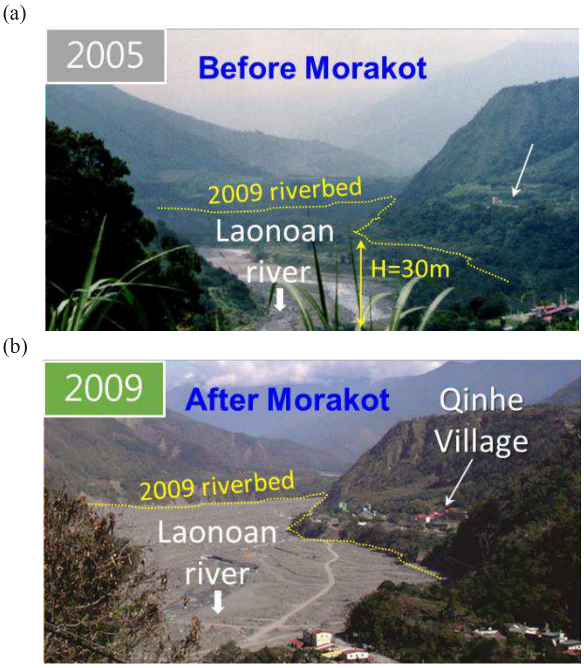

Figure 1. Figure 1-(a) shows a photo of Qinhe village by the river in 2005. Compared with Figure 1-(b), Typhoon Morakot caused river deposition of more than 30m in a short time.

The key factor in the rehabilitation route selection depends on the stability of the passing area. Since this road was built along the Laonong River, the confluence of multiple tributaries along the road, the slope vegetation status in each tributary catchment area will determine the future occurrence of mudflows, rapid river deposition, and dam breaks in dammed lakes, which will further affect the safety of roads. The increasing area of landslides in this catchment area after the disaster was studied and found to be the key factor inducing the river deposition and frequent debris flow. Therefore, to fully understand the compound disasters in this area, macroscopic environmental observation is necessary. The following are the requirements of the survey on this site:

- Quantitative and objective observation methods to be implemented on a regular, repetitive, and long-term basis.
- To be able to conduct in-depth investigations of inaccessible mountainous areas at a relatively low cost.
- To be able to identify various types of disasters at this site and assist in route planning.
- To be able to find out the time when the overall environment is stable and suitable for investment in reconstruction resources.

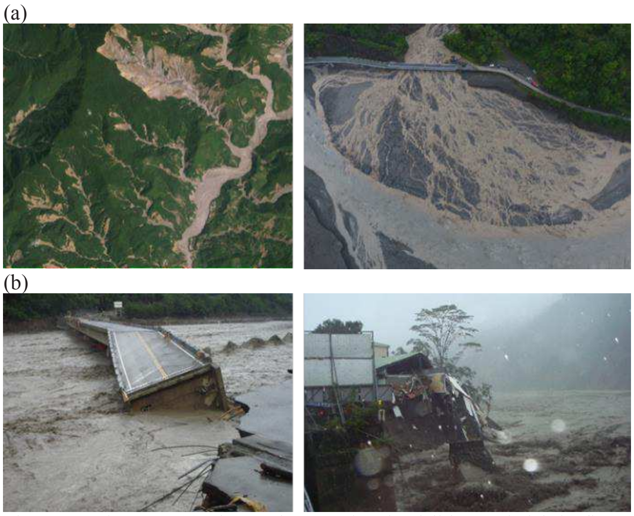

Figure 2. Figure 2-(a) shows the massive landslides and debris flow alluvial fans directly impacted the road built along the river, Figure 2-(b) shows in facing compound disasters, rehabilitation construction became quite difficult and hard to maintain.

3 METHOD

Remote sensing technology is suitable for wide-area observations. In recent years, remote sensing technology has benefited from the development of computer technology and has been able to greatly improve the quality of automatic interpretation. Among them, object-based image interpretation is a very critical development.

Baatz and Schäpe (2000) proposed a high-quality optimized image segmentation algorithm called multi-resolution segmentation, which allows users to classify customized segments. The object-based image interpretation technology can not only use the spectral features of the image, but also incorporate the DTM terrain features into the process of segmentation and classification, so as to improve the accuracy of the landslides zoning and allow a wide range of rapid interpretation of multi-temporal satellite images.

Through the spectral characteristics of satellite images, it is possible to figure out the landslide area with Normalized Difference Vegetation Index (NVDI). This technology is also effective for the changing conditions of river channels and flooding areas.

This method was selected in this research as the main tool of the investigation, in addition to reaching rugged terrain, it can also enlarge the area of survey (see Figure 3).

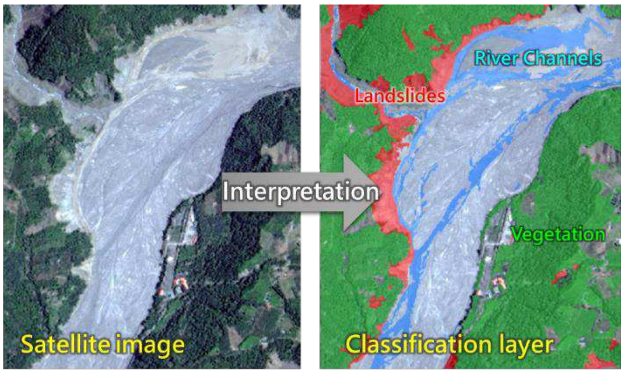

Figure 3. Using object-based image interpretation technology, specific feature information can be obtained quickly and effectively.

This study collected multi-temporal and multi-spectral high-resolution satellite images, covering about 150 km2 three phases per year from 2005 to 2019, for semi-automatic image interpretation. Each image is classified into several thematic features such as vegetation, landslide, river channels, etc. In addition, this research also applied high-resolution LiDAR DEM in zoning the slope units in detail and utilized it as a framework to count the Normalized Landslide Variation Index (NLVI) in each slope unit annually. The NLVI was defined in this study to observe the growth and decline of vegetation and landslide areas in each slope unit.

The analysis process is to convert the classification layer of each year into raster data, assign the attribute value of the landslides grid as 1, and vegetation area as 0, then calculate the difference between raster layers of the two consecutive years. Finally, sum up the grid differences within each slope unit and divide it by the total number of grids within the slop unit as the NLVI, as shown in Eq.1.

$$NLVI = \frac{\sum(value\ of\ later\ raster - former\ raster)}{total\ grid\ of\ each\ slope\ unit} \quad (1)$$

The index is a value between -1 and 1. Close to 1 indicates a greater degree of landslide increase, close to -1 indicates a greater degree of vegetation restoration, and close to 0 indicates that the variation is not significant.

4 RESULTS

NLVI can describe the changes of each slope unit across a specific period. The NLVI during Typhoon Morakot rose significantly, and the slope unit with the highest index reached 0.8, which shows significant changes in slope conditions. In recent years, the NLVI has gradually declined. Most of the slopes initiate the gradual restoration of the vegetation of slopes, and the variation range of the index has also been reduced to the range of ±0.4. It shows that the overall site environment has tended to recover from extreme disasters.

To identify the characteristics of each slope unit in the planning stage, this study additionally considered the landslide rate of each slope unit. The calculation of the landslide rate is often based on the catchment area. In this study, the slope unit is adopted as the statistical unit, as shown in Eq.2. According to the mapping guidelines of environmental geological maps of highway slopes in Taiwan, the current three-degree landslide rate is less than 25%, 25%~50%, and >50% as simple classify.

$$Landslide\ Ratio = \frac{landslide\ grid\ of\ each\ slop\ unit}{total\ grid\ of\ each\ slope\ unit} \times \% \quad (2)$$

Combining NLVI with the landslide ratio, the slope unit can be divided into several specific types by calculating the NLVI and landslide ratio of 368 slope units on this site.

Take NLVI as X and landslide ratio as Y, plot the slope unit as a scatter diagram, mark the average value and $\pm 2\sigma$ of NLVI on the X-axis, and 25% and 50% of landslide ratios on the Y-axis (see Figure 4). Finally, the graph can be divided into (a)~(e) zones. The following features of each type of slope unit are summarized below:

(a) General Type: This type of slope unit accounts for the largest number, which falls into the normal range of variation, and the landslide ratio is below 50%. The condition of this type of slope unit is acceptable, and it should be safe after proper design considerations.

(b) Aggravated Type: Although the landslide ratio is below 50%, it tends to aggravate. In case of a typhoon or heavy rainfall event, it might develop into type (d). It's advisable to strengthen the investigation. Special attention is needed when the route crosses this area.

(c) Recovery Type: The vegetation of this type of slope unit tends to recovery. It should be safe after proper design considerations.

(d) High Landslide Ratio Aggravated Type: This type of slope unit is usually covered with thick collapse deposits and with a high probability to occur again. If it's located in the upper reaches, it may become a source of debris flow material. Crossing through such areas is not recommend, also its downstream areas.

(e) High Landslide Ratio Recovery Type: The vegetation of this type of slope unit tends to recovery. Although the landslide has stabilized, there are still many collapse deposits. If crossing through such areas it is recommended to extend the observation period carefully.

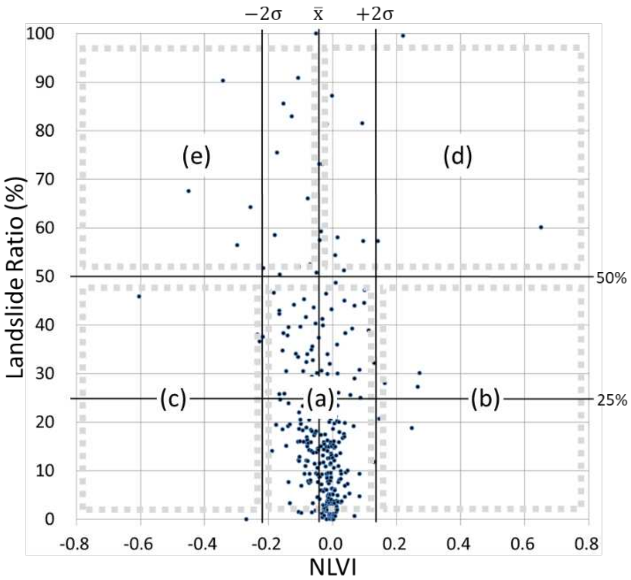

Figure 4. Combining NLVI with the landslide ratio, the slope unit can be divided into several specific types.

From Figure 5, it can be observed that various slope units in this survey area have shown a different tendency of recovery in different time intervals. If you compare the slope units in the tributary catchment areas along the road, it can further show, which catchment area has a high potential for the occurrence of debris flow in the near future.

Through the above analysis process, the following information can be obtained:

- Whether the slope condition of the overall site at this stage tends to be stable.
- Whether the route of the reconstruction project is located in a relatively safe slope unit.
- Whether the current route crosses the confluence of relatively dangerous tributaries.
- Whether it is necessary to consider alternative routes on the opposite side of the river to avoid the impact of debris flow.

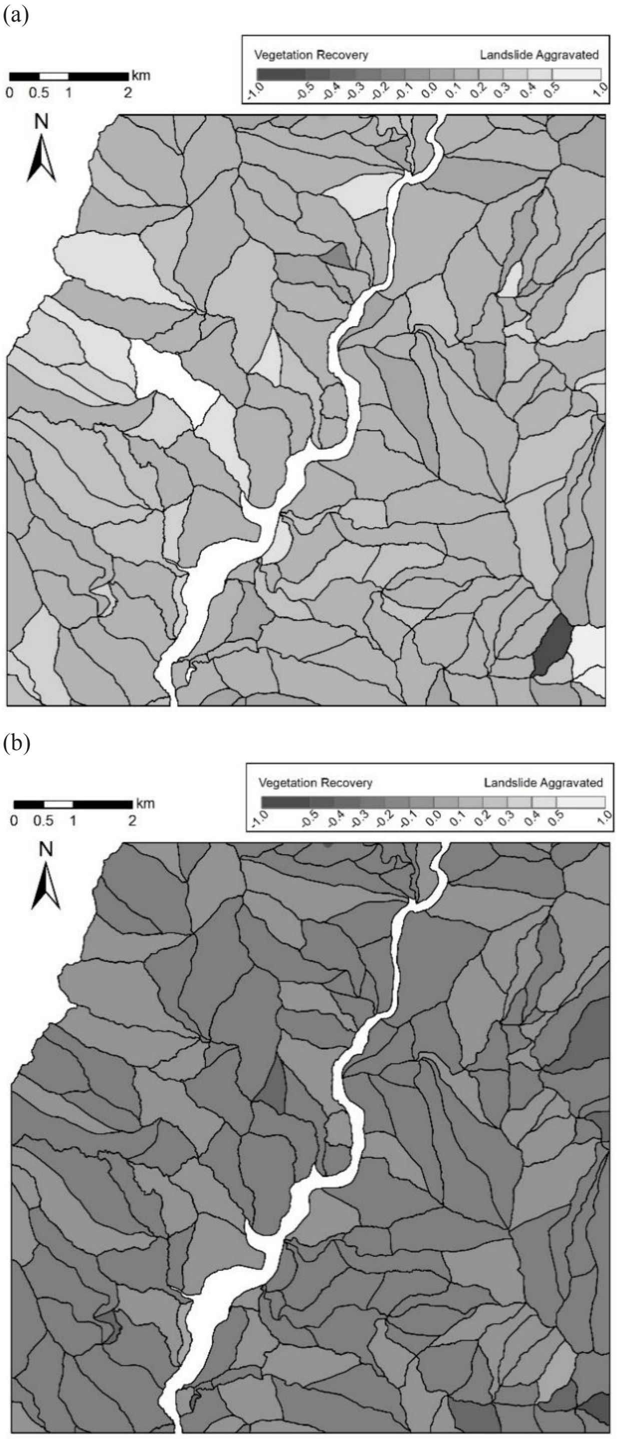

Figure 5. Figure 5-(a) shows the NLVI of the slope units from 2009 to 2010 (across typhoon Morakot). Compared with figure 5-(b), from 2013 to 2014, the vegetation tends to recovery significantly.

5 CONCLUSIONS

This study aims to propose an efficient investigation and evaluation method. By combining advanced remote sensing technology, satellite images and DTM are used for automated rapid interpretation of landslides areas, and the slope unit is used to calculate the vegetation status changes of each unit in a specific time interval. Compared with previous route selection methods, this study improves the range and observation frequency which can more comprehensively identify potential hazards and avoid them. The mid-term rehabilitation road of Qinhe to Fuxing village was repaired in 2017 (see Figure 6). So far, it has successfully withstood several heavy rain events and typhoons. Related environmental investigations are still ongoing annually. This case highlights the following key points:

- The selection of appropriate site investigation methods should be emphasized. In this case, a long-term wide-area survey was selected especially for compound disasters, and the recovery status of the area after a major disaster event was successfully grasped.
- The procedure that carefully assessing the types of disasters and hot spots before investing in post-disaster reconstruction resources can maximize the project benefits and avoid repeated disasters.
- Slowing down the pace of design, long-term surveys, revising survey items, and carefully adjusting route planning annually is a good solution to face an uncertain site environment.

Figure 6. Figure 6-(a). The road alignment was adjusted at the northern end of this section, and several unstable slope units were avoided by lifting the road embankment closer to the river. Figure 6-(b). The viaduct form was selected at the confluence of tributaries to avoid the attack of debris flow. The mid-term road was completed in 2017. After several typhoons and heavy rainfall events in recent years, the road has survived safely.

6 ACKNOWLEDGEMENTS

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