The Landslide Detection in Kaohsiung City using the Integration of Sudden Landslide Identification Produce and Remote Sensing Data

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Abstract: *Taiwan is frequently struck by natural disasters such as typhoons, heavy rainfall, and earthquakes, which often result in severe landslide events. These landslides pose significant threats to human life, infrastructure, and the environment, particularly in regions of Kaohsiung City, where the terrain is complex and risk factors are high. With recurring natural hazards, it is crucial to employ advanced methods for timely and accurate landslide detection.*

This study presents an integrated approach of the Taiwan Data Cube (TWDC) platform with the Sudden Landslide Identification Product (SLIP) model to enhance the detection and analysis of landslides. The TWDC platform supports this approach with the aggregates multiple optical remote sensing dataset. By applying pre-event and post-event satellite imageries, the study processes these data through cloud mask and custom mosaic techniques to ensure that the imagery is clear and suitable for analysis.

The SLIP model plays a critical role in retrieving land coverage changes which is associated with landslides. The model involves the calculation of the Normalized Difference Water Index (NDWI) in both pre-event and post-event satellite images. The difference of NDWI implies the changes in water content and related to soil disturbance. Additionally, a red band Change Vector Analysis (CVA) is applied to detect significant changes in the spectral characteristics of the land surface, which are often associated with landslides.

To further improve the accuracy of landslide identification, SLIP model integrates a Digital Elevation Model (DEM) into the process for the facilitation of slope analysis. The integration of DEM and optical remote sensing data enables the calculations about spectral index differences, CVA, and slope angles. Then the areas affected by landslides could be delineated accurately according to suitable threshold definitions.

After a cross-referenced with disaster data from the Central Weather Administration, the results of the study reveal that the identified landslide areas are primarily located near mountainous and valley regions in Kaohsiung City. These areas are highly susceptible to landslides due to their sensitivity to seismic activity and heavy rainfall. This integration of the advanced remote sensing technology and *sophisticated modeling techniques offers a robust framework for landslide detection. And it contributes to an effective disaster management and mitigation efforts in Taiwan.*

Keywords: Taiwan Data Cube, Sudden Landslide Identification Product, landslide detection, geomatics, satellite images

Introduction

Taiwan is frequently affected by natural disasters such as typhoons, heavy rainfall, and earthquakes, which often lead to severe landslides. An efficient and integrated methodology is needed to detect these disasters in vulnerable regions. This study presents an integrated approach by combining the Taiwan Data Cube (TWDC) platform, which utilizes multiple remote sensing data, with the Sudden Landslide Identification Product (SLIP) model (Fayne et al., 2019) for efficient landslide detection. The methodology involves the use of pre- and post-event satellite images which are processed through cloud mask and custom mosaic techniques in TWDC. The SLIP model facilitates the retrieval of land cover changes by incorporating Normalized Difference Water Index (NDWI) estimations and red band Change Vector Analysis (CVA). Additionally, a digital elevation model (DEM) is integrated into the SLIP model for slope analysis and used to enhance the accuracy of landslide identification. By defining thresholds for spectral index differences, CVA, and slope angles, the system effectively identifies land cover changes indicative of landslides. Analysis of the results that validated by the disaster information from the Central Weather Administration indicates that landslides primarily occur near mountainous and valley areas, closely associated with earthquake and rainfall.

Methodology

This study employs an integrated approach with the capabilities of the Taiwan Data Cube (TWDC) platform and the Sudden Landslide Identification Product (SLIP) model to detect landslides in Taiwan. The methodology consists of several key stages, including data acquisition, pre-processing, landslide detection using the SLIP model.

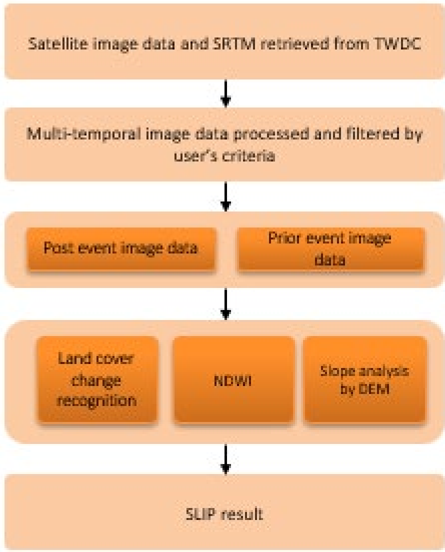


Figure 1: The flow chart of landslide detection using the integration of remote sensing data and SLIP model.

The primary data sources for this study are optical remote sensing images acquired from the TWDC platform. The TWDC aggregates satellite imageries from multiple sensors, providing comprehensive temporal and spatial coverage. For this analysis, pre-event and post-event satellite images are selected to capture the state of the land coverage before and after potential landslide disasters. The satellite images are chosen based on their temporal proximity to significant typhoons, heavy rainfall, and earthquakes reported by the Central Weather Administration, which are known to trigger landslides in the target region.

On the other hand, the analytical optical data is also acquired from open source and business dataset. The well-prepared optical images could be loaded to TWDC database as another data resources for landslide detections.

Data pre-processing is a critical step to ensure the accuracy of landslide detection. The pre-processing workflow for data acquiring from TWDC dataset includes cloud mask, custom mosaic, and image resolution correction. Cloud mask is facilitated according to pixel quality indices (QI) to remove cloud covers and associated shadows from the satellite imageries, which mask the land surface and introduce errors in the analysis. A custom mosaic tool is then applied to get to the union of multi-temporal images and transform them into a single, seamless dataset, ensuring the study area is fully covered by clear pixels. Image resolution correction is conducted to standardize the resolution and image size across remote sensing data acquired from various sensors. This process enables a reliable comparison of pre- and post-event images using SLIP model. The following figure shows the processes of custom mosaic and could mask contribute to a cloud-free image data in TWDC.

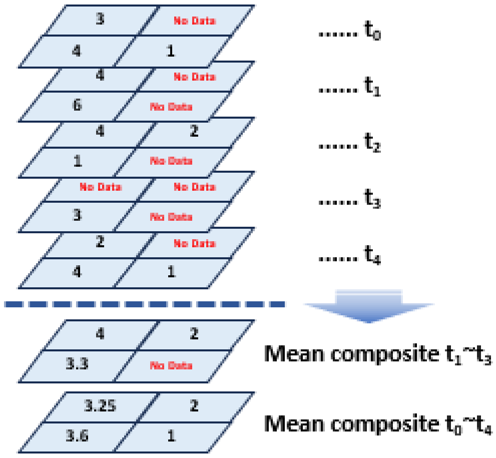


Figure 2: An application of Custom Mosaic and could mask contribute to a cloud-free image data in TWDC.

The Sudden Landslide Identification Product (SLIP) model is applied to the pre-processed imageries to detect area changes affected by landslides. The SLIP model is designed to identify the changes of land cover that are identified as landslides. The process begins with the calculation of the Normalized Difference Water Index (NDWI) for both pre-event and post-event images. Since NDWI is sensitive to changes of water content and can highlight areas where soil moisture has increased due to land movement. The equation of NDWI is shown in the following.

$$\mathrm{NDWI} = \frac{Green - Nir}{Green + Nir} \qquad (1)$$

In Equation (1), *Green* and *Nir* denote the spectral reflectance visible green and near-infrared radiation (NIR) respectively. After NDWIs of pre-event and post-event image data computed, the NDWI difference of pre- and post- event images is estimated as a critical factor of landslide analysis using SLIP model.

In addition to NDWI, the SLIP model concults a Change Vector Analysis (CVA) using the visible red band of the satellite images. CVA detects the shifting in the spectral properties of the land surface and identifies significant changes of vegetation or soil in the study area. These changes often show the relation of landslides, which are triggered by seismic activities and heavy rainfalls. Equation (2) bellow shows CVA calculation using spectral red bands. In this equation, *Red(post)* and *Red(pre)* denote the spectral reflectance visible red in pre-event and post-event images.

$$\text{CVA} = \frac{Red(post) - Red(pre)}{Red(pre)} \qquad (2)$$

To enhance the accuracy of landslide detection, the SLIP model introduces a digital elevation model (DEM) for slope analysis. The DEM provides detailed information about the terrain which is a critical factor for landslide analysis. The information derived from DEM enables the model to assess the steepness of slopes. With the integration of the NDWI difference, CVA, and slope analysis, the SLIP model defines thresholds for study areas and identifies land cover changes. These areas are then classified as potential landslide sites.
In the following, a landslide area monitored by two satellite images and the processes of SLIP analysis is shown in Figure 3. In the pre-event and post-event image data presented as nature color, it is clear to find out land coverage changes after the disaster. To numericize the landslide area, SLIP model with thresholds about red band CVA, NDVI difference and steepness of slope is applied.

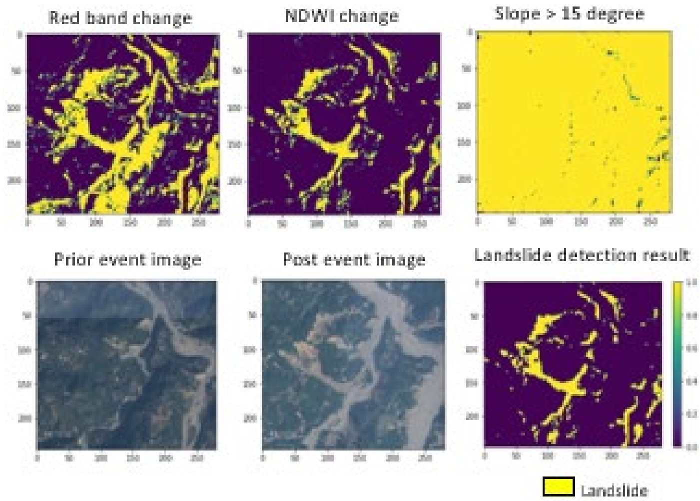


Figure 3: A landslide area monitoring example using optical remote sensing data and SLIP model.

Results and Discussion

This study focuses on mountain area including Liugui, Maolin, Jiasian District in Kaohsiung City due to its highly susceptible to landslides and the sensitivity to seismic activities and heavy rainfalls. The integration of SLIP model and TWDC platform supports regular and emergent landslide detections cover the target area along Xinkai Road in Liugui District. Figure 4 presents the study area in Kaohsiung City.

Figure 4: The study area of the landslide monitoring with longitude: 120.474~120.89, latitude: 22.896~ 23.197.

A landslide analysis by SLIP model includes both pre-event and post-event images, which are crucial for identifying changes of land cover. For a regular landslide detection in Kaohsiung City, the temporal dataset is divided into four phases throughout the year 2023. The divisions capture different periods to observe the impacts of landslides. In the following, four phases in a whole year are defined for analytical period shown in Figure 5.

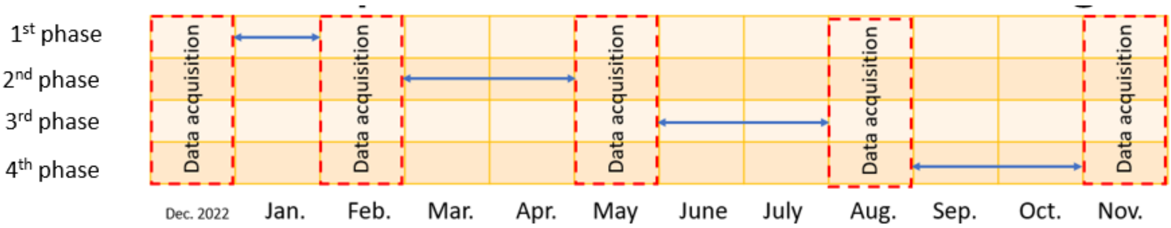


Figure 5: The definition of 4 phases for landslide detection in 2023.

Multi-temporal remote sensing data acquired from Sentinel-2 are applied for the regular analyses in 2023. Due to cloud effect in optical satellite images, cloud mask and custom mosaic techniques are applied to eliminate cloud cover from the imageries that might otherwise obscure the analysis. In the Figure 6, five pre-processed optical images loaded from TWDC are applied for the regular landslide detections.

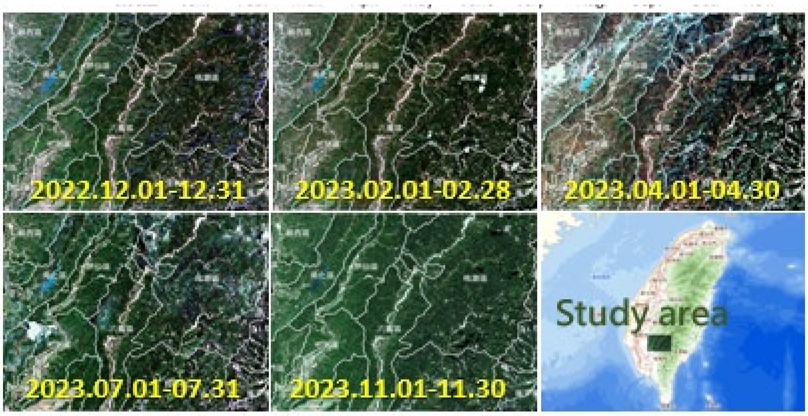


Figure 6: Pre-processed Sentinel-2 image data that covers the target area along Xinkai Road in Kaohsiung City.

The SLIP model is applied to the processed satellite images to detect land cover changes in each phase. The model's methodology included calculating the NDWI and red band CVA from the pre-event and post-event satellite images. These data helped identify changes in moisture content and shifts of vegetation or soil conditions. Here, the thresholds for NDWI difference and red band CVA are defined artificially to be 0.2 and 0.4 respectively. To refine the detection process, the SLIP model also loads DEM data from TWDC to perform slope analysis. In this study, the threshold of slope is defined as 15 degree which is a critical value in target areas with steep gradients.

The results indicate that landslides are primary detected near mountainous and valley regions in the Liugui District, Taoyuan District, and Haiduan Township. The first and second phases of monitoring results show that the incidences of landslides related to earthquakes near Kaohsiung City. The landslides identified in the third and fourth phases in the border area between Taoyuan District and Haiduan Township, as well as in Liugui District might triggered by Doksuri, Khanun, Haikui, and Koinu typhoons. Additionally, the study notes significant landslides in the Laonong River and Qishan River valleys during the fourth phase. Referring to the disaster information derived from Central Weather Administration, the landslides in this phase might be caused by Haikui and Koinu typhoons.

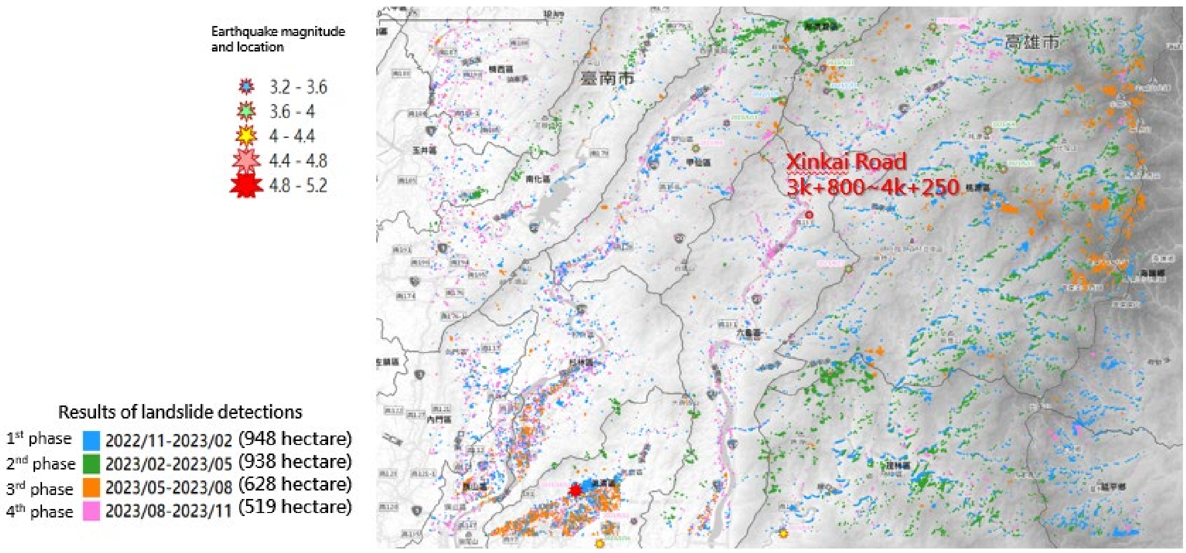


Figure 7: The results of regular landslide monitoring in 2023.

In Figure 7, pixels labels as blue, green, orange and pink present the landslide areas in various phases throughout November 2022 to November 2023. The SLIP model also calculates the affected area in each phase. Comparing the disaster information that announced by Central Weather Administration, Kaohsiung City suffered from various earthquakes during 2023. The locations of landslides are similar to the epicenters. And the areas of landslides show the relation to the magnitude of earthquakes.

For an emergent disaster support, an analysis of landslide for Typhoon Kemi, which significantly impacted Kaohsiung City in July 2024, is shown in the following. Typhoon Kemi had a significant impact on mountainous regions in Kaohsiung City. The typhoon brought intense rainfall and resulted in widespread flooding and landslides. According to news from Central Weather Administration, the Donalin Station in Maolin District recorded an accumulated rainfall of 1,838.5 millimeters from the early hours of July 24th to the morning of July 26th. The rainfall in a single-day on July 25th is 1,217.5 millimeters which ranks as the fifth highest in Taiwanese recorded history. The heavy rainfall led to severe landslides and flows, and hit Namasia and Taoyuan Districts. Meishan, Lavulan, and Fuxing Villages received high alert for landslides and debris flows. The disaster led to a six-day suspension of work and school. There were 107 rivers in Kaohsiung totally issued red alerts for potential debris flows, and 6 large-scale landslide warnings were flagged during typhoon period.

In order to reduce the time consumption and acquire affected area in Kaohsiung City, the high-resolution FORMOSAT-5 products are applied efficiently. Due to sever cloud effect during typhoon period, the FORMOSAT-5 data is processes as Level-4 products artificially. After the atmosphere correction, the original Level-4 products are transformed into top of atmosphere reflectance (TOAR) data to prevent the effects by atmosphere condition. Figure 8 presents FORMOSAT-5 satellite imageries acquisitions before and after Typhoon Kemi in Kaohsiung City. Because sever cloud effects in the post-event image data and the issue about radiometric calibration in FORMOSAT-5 data, TOAR products should be cut into the cloud-free area with same longitude and latitude in GIS platform.

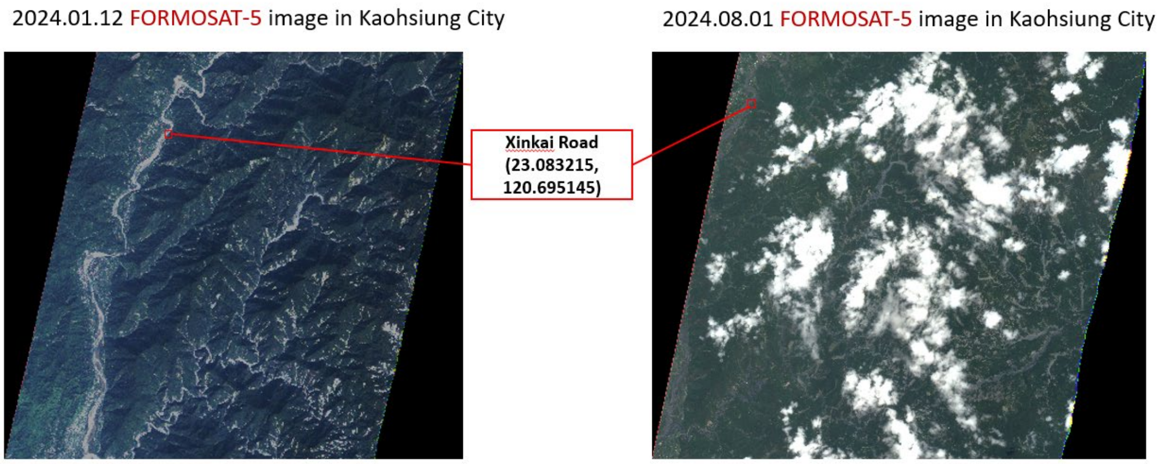


Figure 8: FORMOSAT-5 satellite imageries acquired before and after Typhoon Kemi.

The well-prepared pre- and post-event optical data is loaded to TWDC platform. In this study, the landslide detection focuses on Xinkai Road that is vulnerable for typhoon and strong rainfall due to its soil expose and location. Here, the SLIP model is employed to detect and analyze landslide area by identifying changes in land cover with NDWI and red band CVA analysis to assess moisture levels. This analysis is also further refined by slope gradients evaluation through DEM data that is helpful pinpoint areas most susceptible to landslides. The thresholds of this SLIP model are defined same to the regular detections before.

Considering the locations of watershed near Xinkai Road and disaster events occurred in Liugui District that provided by National Center for Research on Earthquake Engineering, the results revealed significant landscape changes along the Laonong River and its tributaries. These landslide areas are closely aligned with the watershed of Xinkai Road and several disaster events occurred in Liugui District. The SLIP model also successfully identifies large-scale landslides in the Taoyuan and Maolin Districts. The comparison of pre- and post-event images highlighted several critical areas of concern. The model shows significant deformation in the riverbeds of Laonong River. This indicates substantial sediment displacement and river widening due to the landslides and rainfall during Typhoon Kemi period. The result of SLIP analysis about landslide near Xinkai Road is illustrated in Figure 9. In picture (3) of this figure, pixels highlighted as white denote landslide areas. However, with cloud effect in the post-event image that might disturb the landslide detection, pixels labeled as white in the red circles should be ignored from the analysis. A purple area is the location of watershed of Xinkai Road and red spots denote the locations of disasters in Liugui District.

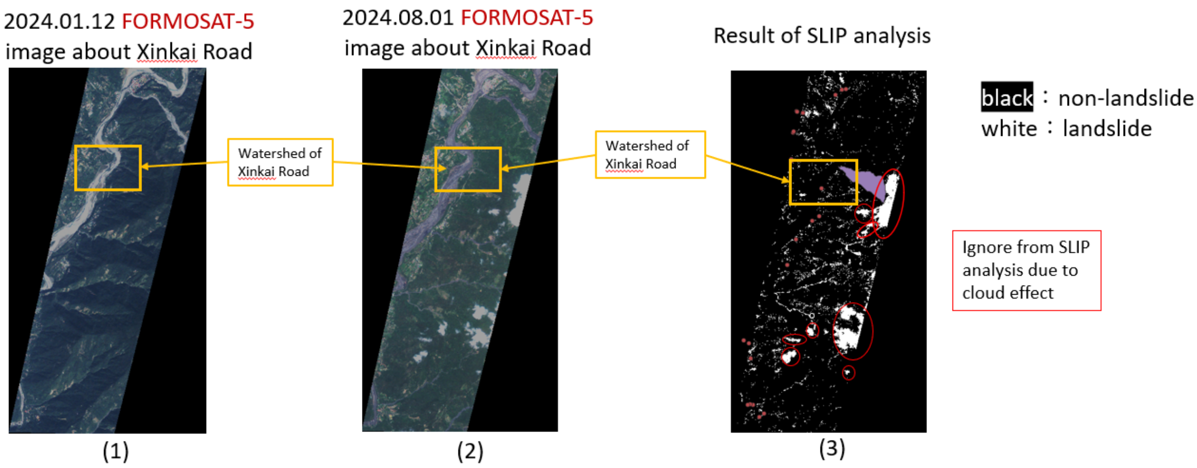


Figure 9: Picture (1) shows pre-event image acquired from FORMOSAT-5 satellite presented by nature color. Picture (2) shows post-event image acquired from FORMOSAT-5 satellite presented by nature color. Picture (3) is the landslide detection using SLIP model.

On the other hand, Sentinel-2 data loaded from TWDC also supports large scale landslide detection for Typhoon Kemi. To overcome the sever cloud effect during typhoon period and acquire a cloud-free post-event optical image, cloud mask and custom mosaic techniques are applied for data preprocesses. Figure 10 presents the preprocessed Sentinel-2 satellite data acquired before and after Typhoon Kemi.

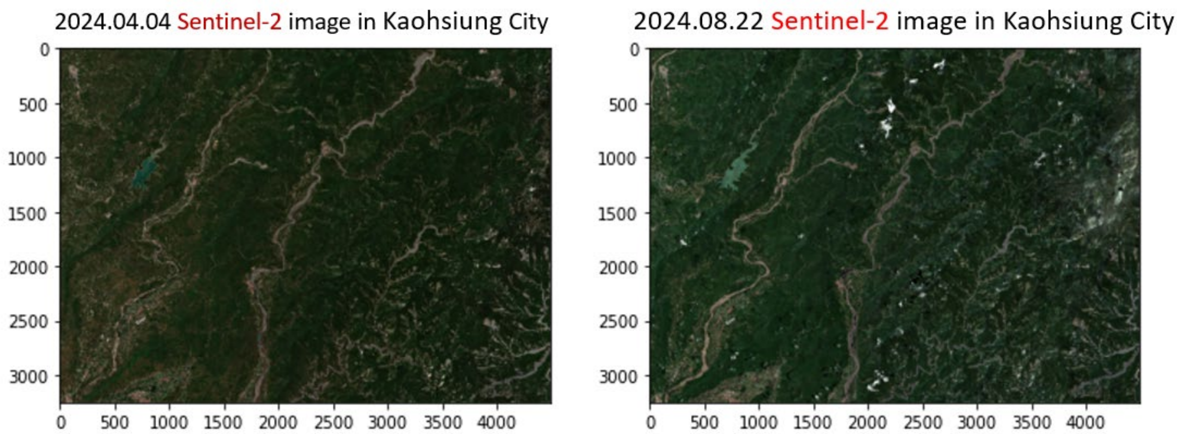


Figure 10: The prior- and post-event Sentinel-2 data that is pre-processes through cloud mask and custom mosaic techniques by TWDC platform.

Then SLIP model facilitates NDWI difference, red band CVA calculations using pre- and post-event Sentinel-2 data. The steepness of slope is also considered using DEM derived from TWDC database. With the default values of thresholds for these three conditions, the result of landslide monitoring in a large-scale area is illustrated using Google map and Google earth as base maps in Figure 11.

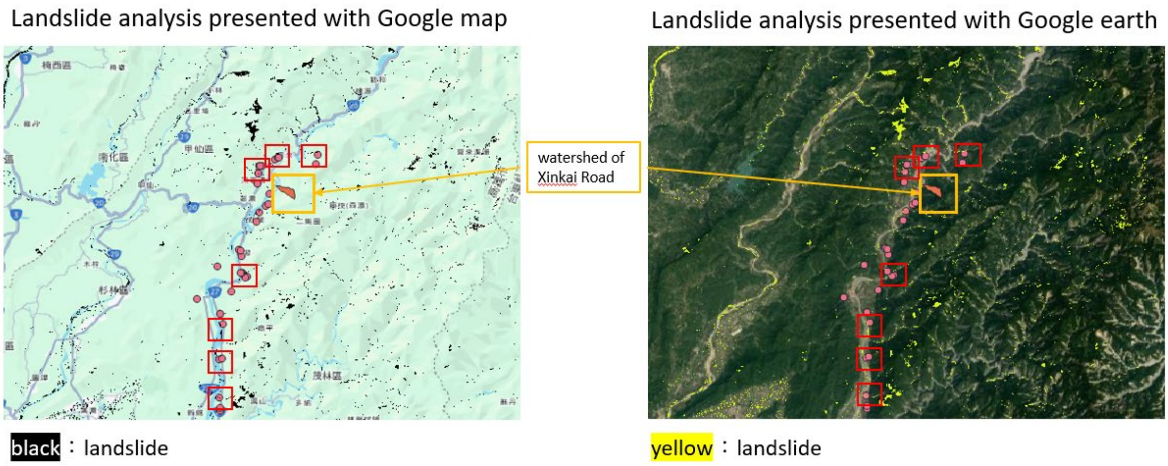


Figure 11: The result of landslide monitoring illustrated using Google map and Google earth as base maps.

The landslide detection presented by Figure 11 shows a similar result to the one estimated using FORMOSAT-5 dataset. Not only the riverbeds and branches of Laonong River, but also the ones of Zengwen River, Houjue River and Nanzixian River show deviations after Typhoon Kemi attacking. The SLIP model also identified large-scale landslides in the Taoyuan and Maolin districts where the terrain is notably steep and vulnerable to rainfall. There are several landslide areas located same to disaster points in Liugui District and labeled by red squares. In the area of watershed near Xinkai Road, landscape changes are also found. This implies the risk of landslide on Xinkai Road.

The SLIP model also supports historical disasters analyses. In the following, an example about the application of landslide detection for a heavy rainfall during 2017 is presented. On June 1st, 2017, Taiwan suffered from the most intense plum rain season which led to significant rainfall across the island. Over the course of several days, the rain caused widespread flooding, landslides, and severe disruption across multiple mountainous regions. This period of rainy season led to some of the highest recorded rainfall levels in recent history, with northern regions experiencing rain accumulations exceeding 600 millimeters in just 12 hours.

The mountainous area in Kaohsiung City was among the most severely affected areas during the 2017 plum rain season. Especially Taoyuan and Namasia Districts faced sever impacts due to the heavy rainfall and subsequent landslides. This intense rainfall led to the swelling of rivers and streams, and caused flash floods that swept through low-lying valleys.

In addition to the flood, the torrential rains triggered numerous landslides which blocked roads and isolated communities. Laonong River and its tributaries showed significant landscape changes and riverbeds widening due to the massive influx of water and sediment. The landslide analysis utilizes multi-temporal and multi-sensors satellite images including LANDSAT-8 and FORMOSAT series data to detect changes in the landscape and identify areas affected by landslides.

For a land coverage change detection using LANDSAT-8 data, images acquired before and after the plum rain season are loaded to SLIP model from TWDC database. In this study, due to the 16-days revisiting for LANDSAT-8 satellite, fewer temporal data is applied for the cloud mask and custom mosaic tools for emergency support. Figure 12 shows the original pre- and post-event LANDSAT-8 data for historical landslide analysis.

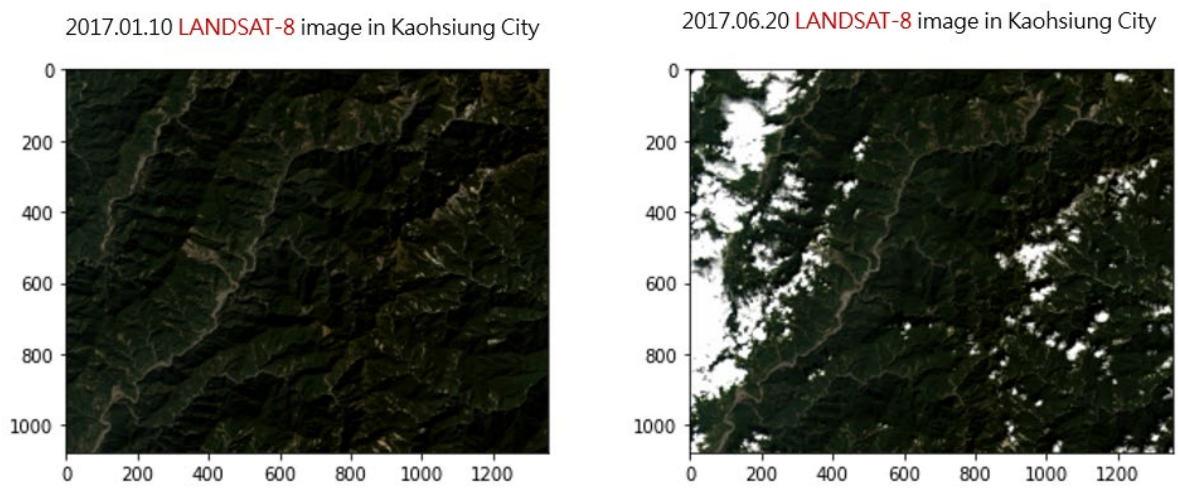


Figure 12: The original pre- and post-event LANDSAT-8 data loaded from TWDC platform.

The result of SLIP analysis shows that the majority of terrain changes occurred along the Nanzixian River and in the mountainous areas near Namasia. A comparison of the SLIP detection with a Google map shows that the areas with significant changes were mostly concentrated around the watershed of Xinkai Road near the Laonong River and its tributaries. Additionally, the SLIP analysis also presents changes along the Southern Cross-Island Highway across the section between Guanshan and Xiangyang. This highway through the mountainous region shows clear signs of instability and terrain changes due to the heavy rainfall and during the plum rain season.

Figure 13 illustrates the results of SLIP analysis using LANDSAT-8 dataset. These regions identified as landscape variations are indicated by the black areas on the SLIP detection output. However, the cloud effects in the left part of the post-event imagery in the blue circle affect SLIP analysis should be ignored. The pink spots and orange area in the lower-left part of the detecting output denote the disasters in Liugui District and watershed of Xinkai Road.

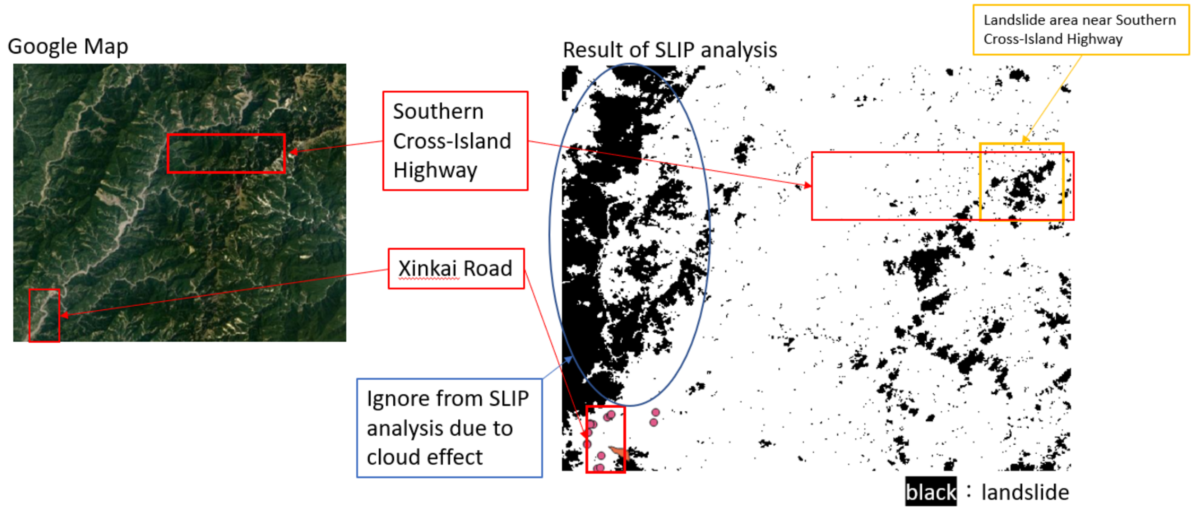


Figure 13: The result of SLIP analysis for plum rain season in 2017 using LANDSAT-8 data.

The case about disaster monitoring of plum rain season in 2017 can also be realized using FORMOSAT-2 and FORMOSAT-5 data as pre- and post-event images for SLIP model. Here, the pre-processed FORMOSAT series data derived from Taiwan Space Agency (TASA) are transformed to TOAR products. After geometric correction in QGIS platform, the imageries are saved as Tiff files in TWDC dataset. Figure 14 illustrates FORMOSAT-2 and FORMOSAT-5 images acquired before and after the plum rain season in 2017.

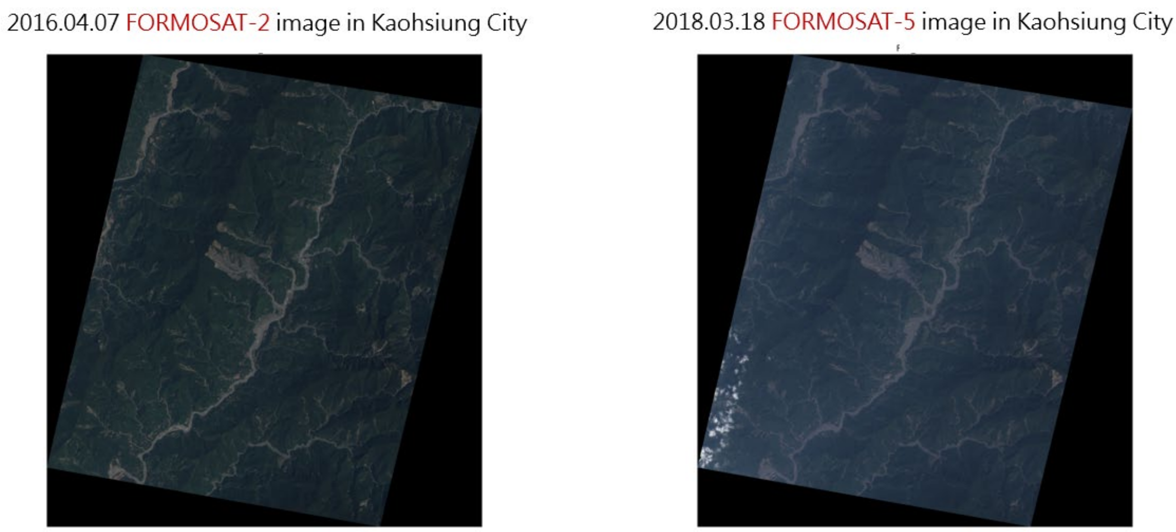
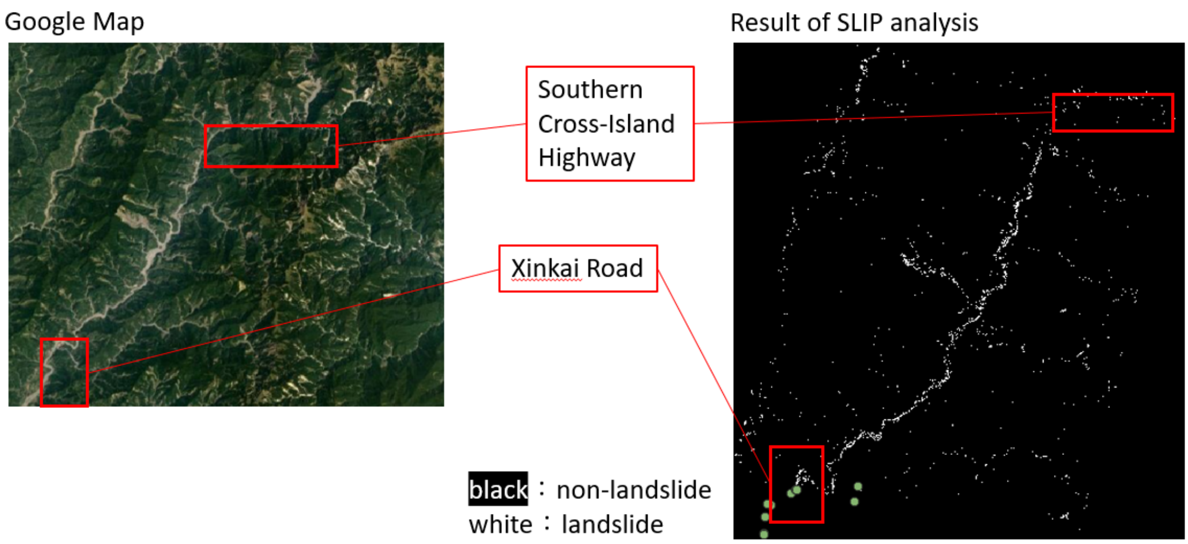


Figure 14: FORMOSAT-2 and FORMOSAT-5 images acquired before and after the plum rain season in 2017.

In the SLIP analysis, because the multi-spectral FORMOSAT-2 and FORMOSAT-5 products contain 8-meter and 4-meter resolutions respectively, the pre-event and post-event images should be resized into the resolution same to FORMOSAT-5 data. Then the NDWI change and red band CVA of two imageries are calculated. The DEM is also introduced to the SLIP model to increase the accuracy of analysis through the threshold of steepness of slope.

The result of landslide detection that compared with Google map as a basemap shows that most of the variations are concentrated around the Laonong River and its adjacent mountainous regions. In particular, two points within the Liugui disaster area exhibit noticeable changes. This indicates possible slope instability or other landscape alterations caused by the heavy rainfall during the 2017 plum rain season. In the following figure, the landscape changes are labeled as white areas. The green spots are the locations of the disaster in Liugui District. In this analysis, nether Southern Cross-Island Highway nor Xinkai Road meet significant changes.



Fugure 15: The result of SLIP analysis for plum rain season in 2017 using FORMOSAT-2 and FORMOSAT-5 data.

Conclusion and Recommendation

The combined analysis of natural disasters' impact on Kaohsiung City using the TWDC platform and the SLIP model provides insights into the effectiveness of advanced geospatial technologies for landslide monitoring and response. The study demonstrates that the integration of multi-temporal optical satellite images with advanced analytical models can support landslide detection for complex and unstable terrains in an efficient way.

Kaohsiung City, particularly in mountainous areas like Maolin, Taoyuan, and Namasia Districts, with steep slopes and proximity to riverbeds makes the terrains highly susceptible to landslides. For an emergent disaster support during typhoon and plum rain period, the integration of SLIP model and TWDC effectively detected these landscape changes by analyzing pre- and post-event satellite images. The result of detection reveals extensive riverbed widening and land cover change.

The results in this study confirm that the areas labeled by the SLIP model for potential landslide risks relate to the disaster reports from Central Weather Administration. Furthermore, the inclusion of DEM data in the analysis provided critical insights into the role of slope gradients in landslide and further enhances the model's accuracy.

Based on the applications of TWDC and the SLIP model in this study, several recommendations are proposed to enhance disaster monitoring and management in the following.

The strategy about the integration of TWDC and SLIP should be extended to cover additional regions with similar geological characteristics that are prone to landslides. The expansion of the monitoring scope will provide a more comprehensive understanding about landslide risks and improve disaster management.

On the other hand, continued research for refining the SLIP model could be the incorporation with additional environmental variables such as real-time rainfall data, soil moisture levels, and aspects that might be shared by governmental disaster management agencies. Ongoing research will enhance the model's accuracy and provide a more understanding of landslide dynamics.

Furthermore, the landslide analysis on TWDC platform could be a further integration to Remote Procedure Call (RPC) technology. The development of RPC technology within the TWDC and SLIP frameworks facilitate real-time data sharing and communication with other GIS platforms for governmental authorities. This technology might enable rapid decision-making according to critical information during disaster events.

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