Application of InSAR technology to investigate the surface deformation of the 0403 Hualien seismic series

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1. Introduction

Taiwan, located at the convergent boundary between the Eurasian Plate and the Philippine Sea Plate, is one of the most seismically active regions in the world. The ongoing collision between these tectonic plates generates significant geological stress, resulting in frequent earthquakes. Hualien, located in eastern Taiwan, is particularly vulnerable to seismic activity due to its proximity to the plate boundary. The region often experiences intense earthquake sequences, including mainshocks and aftershocks that can trigger extensive surface deformation.

On the morning of April 3, 2024, a powerful earthquake with a magnitude of 7.2 struck the offshore region near Hualien. The earthquake occurred at a shallow focal depth of 22.5 kilometers and was caused by a thrust fault trending in the northeast-southwest direction. The event generated substantial vertical and horizontal ground displacement. In addition to the mainshock, the earthquake triggered hundreds of aftershocks, some exceeding magnitude 6. These aftershocks contributed to further surface deformation, complicating the seismic hazard profile in the region.

Surface deformation caused by earthquakes can have significant implications for infrastructure, human settlements, and natural landscapes. Monitoring and analyzing such deformation is critical for understanding fault dynamics, stress redistribution, and seismic risk. This study aims to apply Interferometric Synthetic Aperture Radar (InSAR) technology to investigate the surface deformation resulting from the 0403 Hualien seismic series. By utilizing both Differential Interferometric Synthetic Aperture Radar (DInSAR) and Persistent Scatterer Interferometry (PSInSAR) techniques, the study seeks to capture both immediate co-seismic deformation and long-term post-seismic displacement patterns.

These findings will enhance our understanding of the ongoing tectonic activity in the region and inform future seismic hazard assessments.

2. MATERIALS AND METHODS [Heading ← 12pt, Times New Roman, bold, Line space: after 6pt]

InSAR technology has become a widely used tool for measuring surface deformation, especially in areas prone to earthquakes. The two primary InSAR methods used in this study are DInSAR and PSInSAR, each offering unique advantages in capturing different types of deformation. DInSAR is particularly effective for observing co-seismic deformation, while PSInSAR provides detailed insights into the post-seismic and inter-seismic phases of fault activity.

DInSAR operates by comparing radar images taken before and after a seismic event. In this study, radar images from the European Space Agency's Sentinel-1 satellite were used. These images were taken at different time intervals, both before and after the April 3 earthquake, to capture the immediate co-seismic deformation. DInSAR works by measuring the phase shift between radar signals, which corresponds to ground displacement. By comparing pre- and post-earthquake images, we can detect the amount of vertical and horizontal movement that occurred during the earthquake. This technique is particularly valuable for detecting large-scale deformation patterns over fault zones.

PSInSAR, on the other hand, is a time-series analysis technique that tracks the movement of persistent scatterers—stable points on the ground that consistently reflect radar signals. These points, often located on man-made structures or natural features, allow for continuous monitoring of ground displacement over an extended period. PSInSAR is especially useful for detecting slow and gradual deformations that may not be immediately apparent in DInSAR analysis. By utilizing a series of radar images taken over several months, PSInSAR can reveal the cumulative effects of aftershocks and other tectonic processes that contribute to long-term surface deformation.

The study area focuses on the Hualien region, where both the mainshock and the subsequent aftershocks occurred. To enhance the accuracy of the InSAR measurements, additional data from ground-based GPS stations were integrated into the analysis. The GPS data provided high-resolution measurements of horizontal displacement, complementing the vertical deformation data captured by the InSAR techniques. The combination of satellite and ground-based data provides a comprehensive view of the surface deformation and allows for more precise modeling of fault movement.

3. Results and Discussion

Given the nature of the April 3 earthquake, it is anticipated that the primary surface deformation will consist of significant vertical uplift and subsidence along the fault line. The thrust fault mechanism that caused the earthquake typically results in vertical displacement, with areas on one side of the fault being pushed upward while areas on the other side subside. DInSAR analysis is expected to reveal these patterns of uplift and subsidence, with the most pronounced deformation occurring near the epicenter of the earthquake. The vertical displacement could be on the order of several meters, particularly in regions closest to the fault rupture.

In addition to the mainshock, the aftershocks will contribute to further deformation. The frequent aftershocks following the April 3 earthquake are likely to cause additional localized uplift and subsidence, which may accumulate over time. PSInSAR will play a crucial role in capturing the gradual deformation caused by these aftershocks. By analyzing a time series of radar images, we expect to observe continuous displacement that reflects the long-term impact of both the mainshock and the aftershocks.

One of the key advantages of using InSAR technology is its ability to detect subtle deformations that may not be immediately visible on the ground. Even small aftershocks can generate measurable ground displacement, and these movements can provide important clues about the stress redistribution occurring within the fault system. By combining DInSAR and PSInSAR, we can gain a more detailed understanding of how the fault system evolves over time and how seismic activity affects the broader tectonic environment.

The frequent aftershocks observed in the Hualien region suggest that the stress changes caused by the mainshock may have reactivated nearby faults or increased the likelihood of future seismic events. PSInSAR, with its ability to track slow deformation over time, will help identify areas where the fault system remains active. This information will be crucial for assessing the long-term seismic hazard in the region.

In addition to vertical deformation, horizontal movements are also expected to occur. While InSAR is most effective at detecting vertical displacement, the integration of GPS data will allow us to estimate the horizontal components of ground movement. This combined approach will provide a more complete picture of how the 0403 earthquake series affected the region.

4. Conclusion and Recommendation

The application of InSAR technology, particularly the combined use of DInSAR and PSInSAR, offers a comprehensive approach to studying earthquake-induced surface deformation. This study of the 0403 Hualien earthquake series will provide valuable insights into the complex interactions between faults and how seismic activity influences surface deformation over time. The results will contribute to a better understanding of fault dynamics, stress redistribution, and the potential for triggering future seismic events.

The findings of this study have practical implications for earthquake preparedness and hazard mitigation in Taiwan. By identifying areas of significant surface deformation and tracking the evolution of fault activity, authorities can make more informed decisions about infrastructure planning and disaster response. The ability to detect subtle ground movements using InSAR technology also opens up new possibilities for early warning systems, which could provide critical time for residents to evacuate or take protective measures in the event of a future earthquake.

Looking ahead, it is recommended that future research continue to integrate satellite-based InSAR data with ground-based measurements such as GPS and seismic sensors. This combined approach will improve the accuracy of deformation monitoring and enhance our ability to predict seismic hazards. Additionally, advances in satellite technology, such as the launch of higher-resolution radar satellites, will further improve our ability to detect even smaller deformations and refine our understanding of fault behavior.

In conclusion, the insights gained from this study should be used to inform earthquake preparedness strategies and disaster mitigation efforts in Taiwan and other seismically active regions. By understanding the patterns of surface deformation and fault activity, authorities can take proactive measures to reduce the risk of damage and loss of life. InSAR technology has the potential to revolutionize the study of earthquakes, and its continued application in regions like Taiwan will be essential for advancing our understanding of the Earth’s dynamic processes.

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