DEFORMATION MONITORING AND ANALYSIS OF CIVIL ENGINEERING STRUCTURES USING INSAR AND GIS

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ABSTRACT: After more than 70 years of construction, Taiwan has gradually built a convenient living environment while driven by industry development and economic prosperity. The contribution of public construction is undoubtedly vital to a modern society. However, many civil engineering infrastructures, such as bridges, electric power transmission towers and dams, constructed decades ago have been gradually affected by natural hazards and environmental factors such as earthquakes, typhoons, heavy rainfalls, land subsidence, soil liquefaction and materials deterioration. Those infrastructures are going into the recession of their life cycle. The government has put a great effort to the maintenance and monitoring of infrastructures in recent years, with goals to extend the life of the structures and also to ensure public safety.

In recent years, radar imaging for commercial and scientific applications have been adopted in many disciplines and various applications were launched and carried out successfully. Synthetic Aperture Radar (SAR) is a microwave-based active imaging system that can be mounted onboard an aircraft or a satellite. Because SAR is less affected by weather, it has been widely used in environmental and disaster monitoring and investigations. This paper describes a systematic approach to analyze the deformation of several engineering structures using Persistent Scatterers Interferometric Synthetic Aperture Radar (PSInSAR) technology with multi-temporal Sentinel-1 data. The results indicate that the correlation coefficient between PSInSAR and GPS observations among the examples presented in this paper is up to 0.7 and the root-mean square error (RMSE) is 23.9 cm. Furthermore, with the help of GIS, this study also develops a Web application with Geospatial database that allows users to make a convenient searching and analysis for rapid screening of potential severe subsidence or deformation areas and targets to help decision making.

1. THE DEMAND OF CIVIL ENGINEERING STRUCTURES DEFORMATION MONITORING

Because of the extreme weather in recent years, the challenge in the safety of public infrastructure becomes more and more severe. Taking bridges in Taiwan as instance, affected by natural disaster, such as earthquake, typhoon, heavy rainfall, and soil liquefaction and material aging, these bridges are getting into a recession period in the life cycle. According to a bridge survey conducted by the government, the result shows that subsidence and deformation are found among some bridges. For example, an abnormal hinge sinking has been noticed on the Yuanshan Bridge of National Highway No. 1 since 1978. The hinge sinking was up to 62.9 cm in 1992 and is suspected continuing. Besides natural disasters, anthropic factor is also a disservice to infrastructure. Groundwater extraction causes severe ground subsidence in Changhua, Yunlin, Chiayi and Pingtung. The long term analysis result of ground monitoring conducted by the Water Resources Agency indicates that there is up to 160 cm subsiding around Tuku and Yuanchang in Yunlin County in recent 20 years. The greatest subsiding rates is 5.6 cm per year, and the most significantly subsiding area is about 104.9 km^2, as shown in Figure 1. Figure 1 also shows that the high-speed railway passes through the most significant subsiding area. Although the current pier angle variable is 0.415/1500 which is within the acceptable value of 1/1500, the subsiding still need to be monitored constantly.

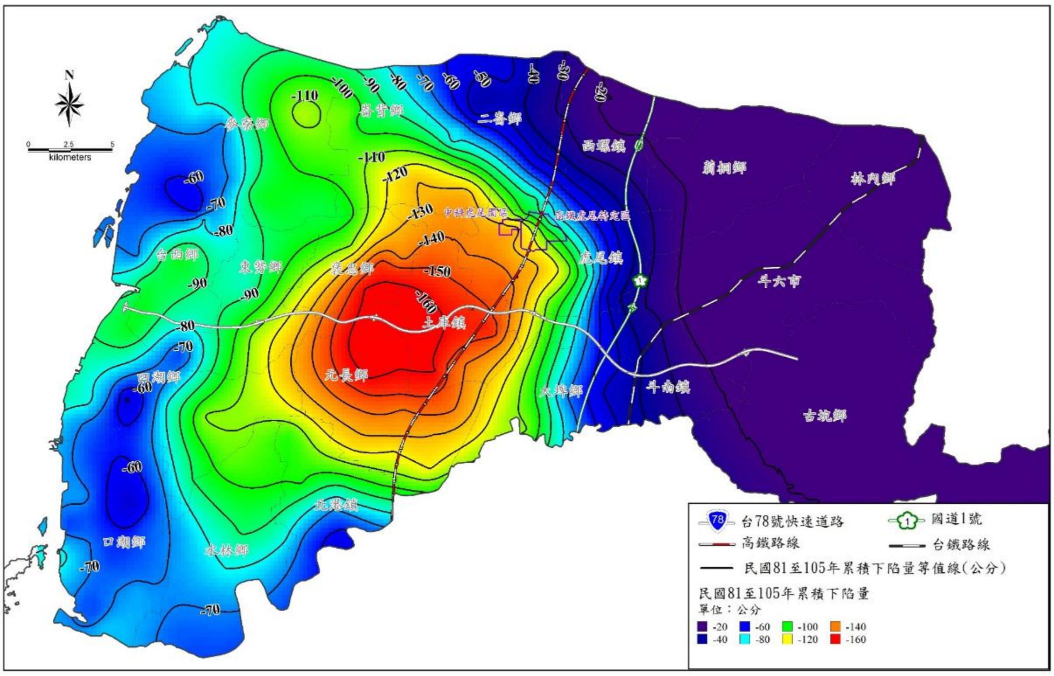

Figure 1. Subsidence in Yunlin from 1992 to 2016.

Currently, the method of long-term ground monitoring is using in-situ survey, GPS tracking station, land subsidence monitoring well, etc., to estimate facet subsiding trend with these point and linear leveling data. However, due to the financial restriction, it is difficult to take a comprehensive survey for a large area. Therefore, this study uses Interferometric Synthetic Aperture Radar (InSAR) technique which can be applied to regional ground monitoring more economically.

2. CURRENT DEVELOPMENT OF InSAR TECHNIQUE

Remote sensing has advanced rapidly recently. Differential Interferometric Synthetic Aperture Radar (DInSAR) is one of the common methods for large-area ground monitoring. The basic idea of DInSAR is to observe the changes of the phases of radar waves between different measurements at the same location and from the same orbit. The ground changing would cause the phase difference of the radar wave, and the line-of-sight (LOS) displacement can be derived from the phase difference. However, it is difficult to reduce the noises in InSAR measurements. Hence, Multi Temporal InSAR (MT-InSAR) which can provide high density facet information with the elevation precision up to centimeter level is developed. There are several implementations for MT-InSAR, including Small BAseline Subset algorithm (SBAS), Temporarily Coherent Point InSAR (TCP-InSAR), and Persistent Scatterer InSAR (PS-InSAR). The concept of PS-InSAR is using ground featured objects which can scatter radar wave stably as PS points (Ferretti et al., 2000; Hooper et al., 2004). The signal of a PS point in radar image is stable and consistent (Figure 2.) and has better signal-to-noise ratio comparing to non-PS point.

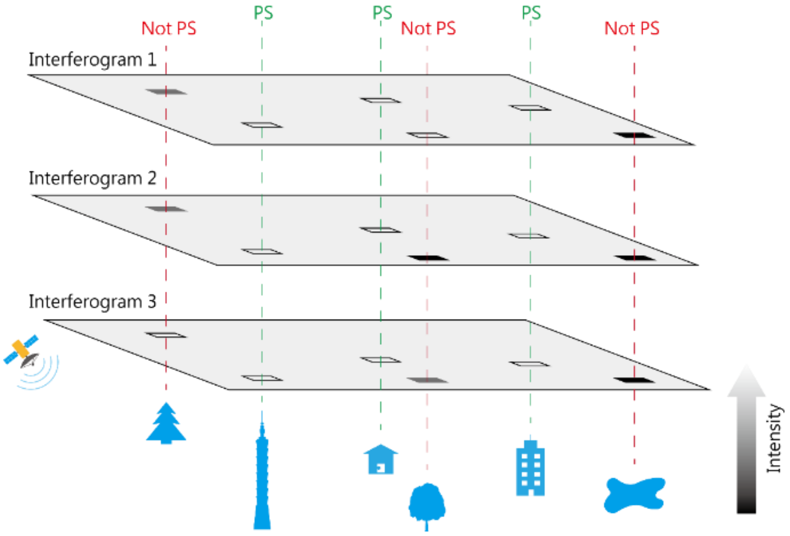

Figure 2. PS point in PS-InSAR.

Because of its high reliability, PS-InSAR is the main technique used for deformation monitoring in this paper. Multi-temporal radar images from different sources such as Sentinel-1, ALOS PALSAR and TerraSAR-X are used to evaluate the subsiding of entire Taiwan, and 539 long-term GPS stations provided by the Academia Sinica are used to verify the PS-InSAR results. The obtained PS-InSAR data are imported into a geospatial database for subsequent spatial analysis.

3. MONITORING MODEL DESIGN

The results of radar image calculation are import into a geospatial database (SQL server) which has topology and the displacement of ground elevation in the LOS direction. In addition, the multi-layer architecture is applied in this research to calculate the changing rate (Figure 3.) to identify severely changed area. The architecture can also calculate certain cases through radar images in different bands and different algorithms.

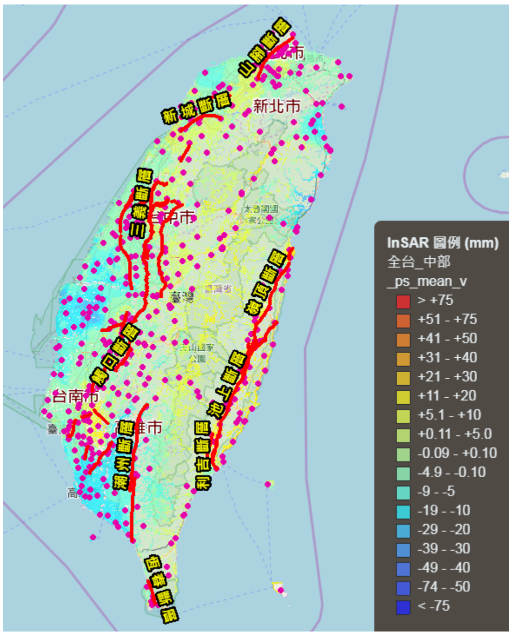

Figure 3. Ground changing rate map of Taiwan calculated from 4-years of descending Sentinel-1 data.

4. CASE IMPLEMENTATION OF PS-InSAR

In this paper, PS-InSAR is applied to deformation monitoring and analysis of civil engineering structures on Yunlin high-speed railway and Central Taiwan Science Park at Huwei. TerraSAR-X data are used in the case analysis of Yunlin high-speed railway. The image resolution is 2.2 m, using X-band, and there are 24 descending images acquired from 7th Aug 2014 to 1st Mar 2016. The result is displayed in Figure 4, showing the line of sight velocity in mm/year. In Figure 4, positive values indicate that the ground is uplifting. On the other hand, negative value means subsidence (rate) of the ground.

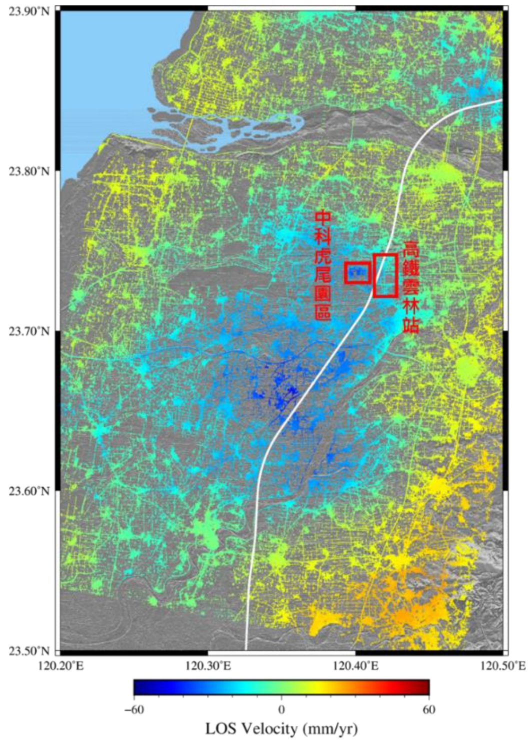

Figure 4. The velocity map in line of sight on Yunlin high-speed railway. (White line is high-speed railway and red squares are Central Taiwan Science Park at Huwei and high-speed rail station)

Figure 4 shows that there is a subsidence near Yunlin high-speed rail station. Along the high-speed railway, we can see the subsidence around Yunlin high-speed rail station through PS-InSAR. The time series results are shown in Figure 5.

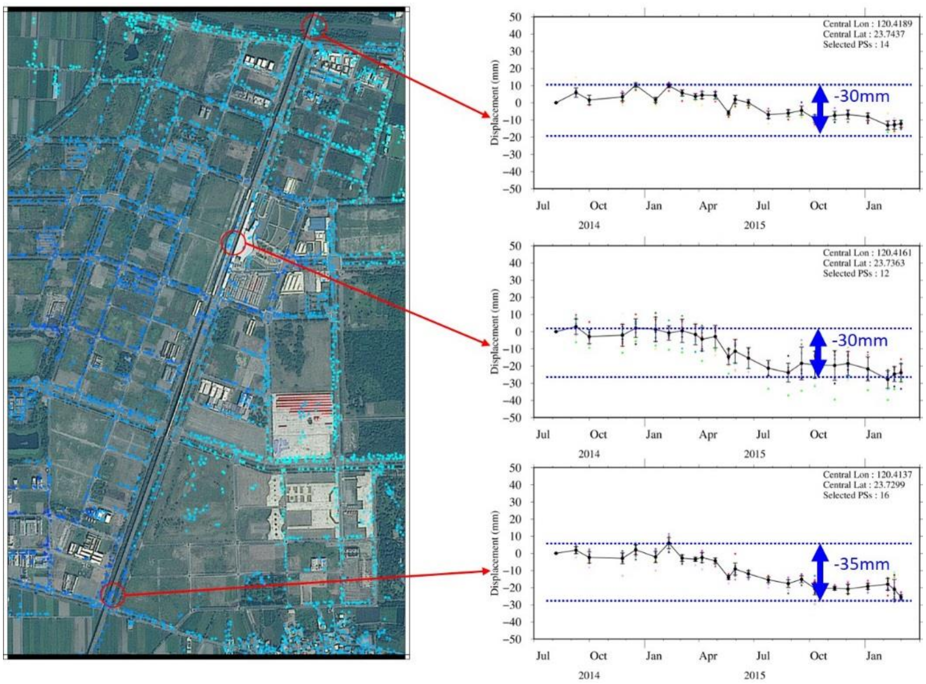

Figure 5. Time series of displacement at Yunlin high-speed rail station and at both ends along the railway.

Figure 5 indicates that all three locations subside; the displacements are up to 30 to 35 mm. Furthermore, according to Figure 4, there is a subsidence in Central Taiwan Science Park at Huwei. PS-InSAR results of two buildings in this area are shown in Figure 6. Similar to Yunlin high-speed rail station, Central Taiwan Science Park at Huwei also has subsidence but more severe. The largest displacement is up to 55 mm. This case demonstrates that using the X-band TerraSAR-X images with PS-InSAR analysis is an effective approach for monitoring displacement of transportation structures and built-up areas.

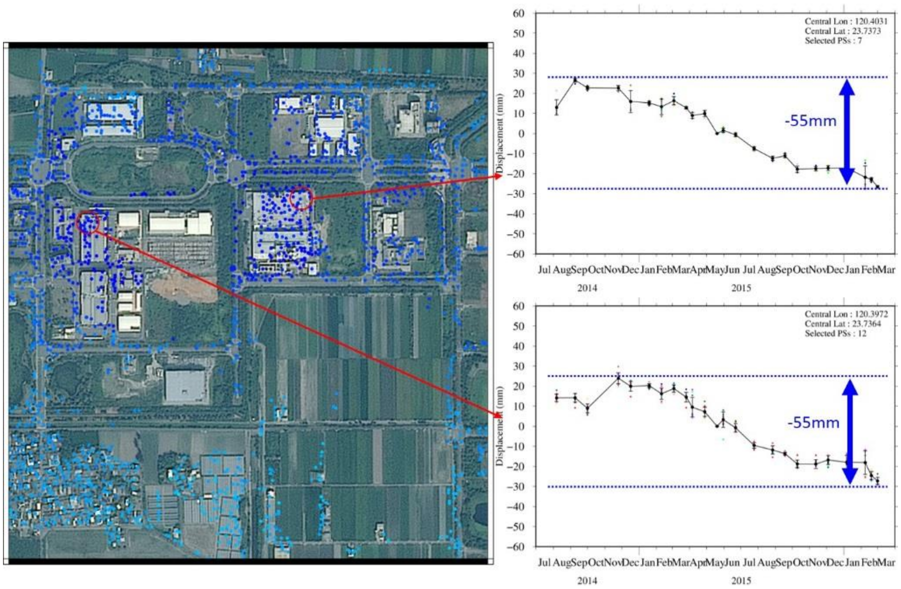

Figure 6. Time series of displacement in Central Taiwan Science Park at Huwei

5. Spatial Analysis

A land monitoring platform is developed in this research. The platform includes abundant geospatial data such as InSAR monitoring data, remote sensing images, Taiwan Geospatial One Stop base maps, digital elevation models, geology database, natural disaster database and GPS data from different government agencies. There are many functions in the GIS platform including point and cross-section InSAR deformation plotting, GPS elevation displacement trend plotting and earthquake and typhoon data comparison. With the geospatial data and the platform, users can overlay the data to perform more sophisticated analyses.

Taking the Central Taiwan Science Park at Huwei as an example, we can see that there is a great subsidence around Yunlin area base on Figure 3. Users can also zoom to the Central Taiwan Science Park at Huwei and inspect the point information which has GPS long-term observations (Kuo, 2018), as shown in Figure 7 (light-blue line: original InSAR deformation, blue line: InSAR fitting line, red line: GPS fitting line, green line: earthquake).

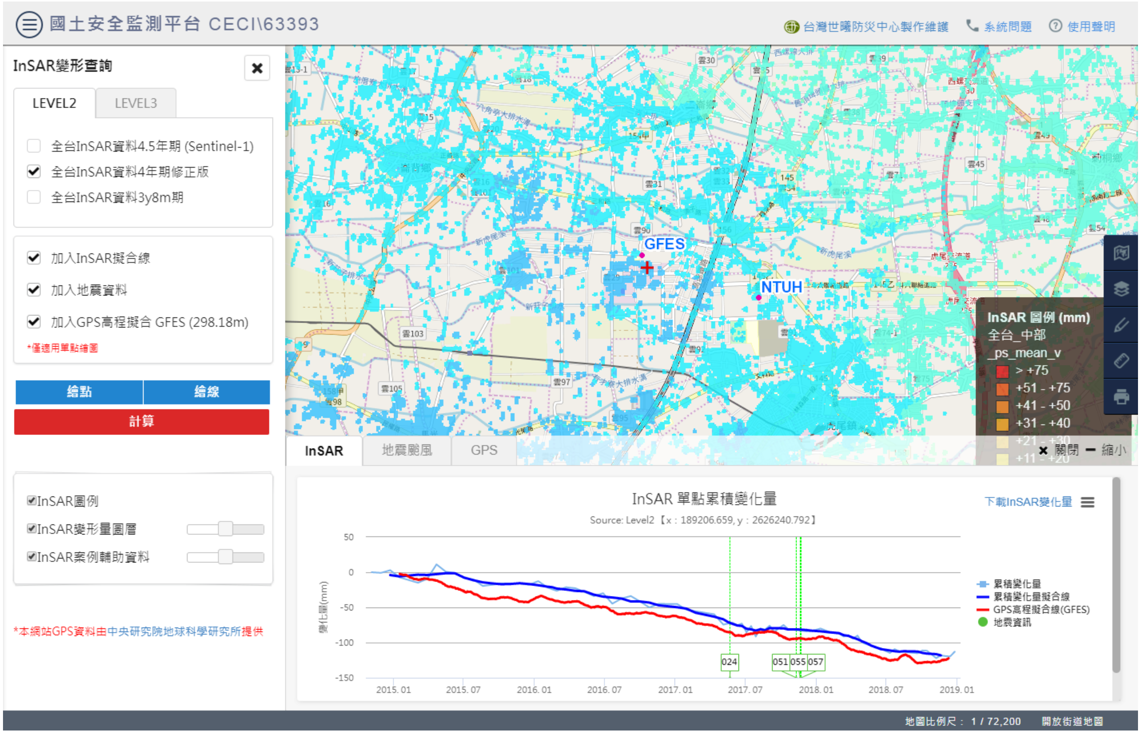

Figure 7. Viewing deformation information in Land monitoring platform

In Figure 7, the light blue line is the PS-InSAR time series of displacement for four years calculated from Sentinel-1 data. There is a continuing subsiding trend in Central Taiwan Science Park at Huwei; the displacement is up to 12 cm for four years. Compared with the GPS data (red line) (Kuo, 2018), the displacement result from PS-InSAR has a high correlation with GPS observations. This proves PS-InSAR is appropriate for deformation monitoring to understand the ground change which can be critical for evaluation in civil engineneering.

6. CONCLUSIONS

In this paper, PS-InSAR is used to help deformation monitoring and analysis. It demonstrates that radar remote sensing technique is appropriate for large-area monitoring. As stated above, there are several conclusions list below:

1. InSAR can be applied to large-area deformation monitoring. Using time series deformation displacement, the trend and situation can be understood and controlled.
2. Radar images in different bands are adopted, including Sentinel-1, TerraSAR-X and ALOS PALSAR, for InSAR analysis. The results are imported into a database so users can search and analyze by multi-layer architecture, then filter the data by spatial criteria to obtain appropriate information.
3. The TerraSAR-X PS-InSAR analysis results for Yunlin high-speed rail station and Central Taiwan Science Park at Huwei indicate that the area is continuously subsiding. The displacement is up to 30 to 35 mm in 1.5 years at Yunlin high-speed rail station and 55 mm at Central Taiwan Science Park at Huwei. The case demonstrates that PS-InSAR analysis of X-band SAR images can help understand the deformation of transportation structures and built-up areas.
4. The displacement from PS-InSAR is up to 12 cm for four years which is highly co-related with GPS observations.

This proves that InSAR is accurate enough for deformation monitoring.

5. The GIS platform can help users overlay different layers such as open data, with many functions and modules. Users can search and analyze based on different spatial criteria for efficient decision making support.
6. With the concept of Big Data and information platform, the developed land monitoring platform can be used as a tool for disaster prevention in large-area land monitoring. A mobile version is under development in order to achieve "Smart Land" and "Intelligent disaster prevention".

7. REFERENCES

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