Integrated use of GNSS and InSAR Techniques for Movement Monitoring under Trunk Road T2 and Cha Kwo Ling Tunnel

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ABSTRACT

In the Trunk Road T2 and Cha Kwo Ling Tunnel (collectively "the T2") project, a number of innovative techniques have been employed successfully. In particular, the Global Navigation Satellite System (GNSS) and Interferometric Synthetic Aperture Radar (InSAR) have proven to be beneficial in enhancing productivity and site safety for movement monitoring of sensitive receivers during the course of tunnel works in the T2 project. This paper reports the site application of these two innovative techniques in this tunnel project and the results of the GNSS and InSAR monitoring works. GNSS monitoring was applied to monitor the movement of the existing Public Works Central Laboratory (PWCL) Building due to the Tunnel Boring Machine (TBM) launching shaft construction works in close proximity and the movement of the seawalls and breakwater due to the crossing of TBMs underneath these marine structures, whereas InSAR monitoring was used to monitor the settlement of the existing structures in Cha Kwo Ling Village due to the T2 tunnel works. It is demonstrated that both GNSS and InSAR monitoring can effectively supplement the conventional survey monitoring.

Keywords: GNSS, InSAR, Movement monitoring

1 Introduction

With the recent advancement in satellite technology and data analytics, a remarkable opportunity to employ innovative solutions in construction projects has been unleashed in recent years. Both GNSS and InSAR are innovative techniques for monitoring purpose, involving the use of satellites for movement or deformation monitoring with high precision and accuracy, for application under different site scenarios or site constraints. GNSS can offer accurate real-time 3D movement monitoring at specific locations on site, whilst InSAR is a remote sensing technology which is suitable for monitoring deformation over large areas owing to its large spatial coverage.

In the T2 project, the GNSS-based monitoring system was established to achieve real-time and fully automatic monitoring of 3D movements of various sensitive receivers, which include the PWCL Building, the Kwun Tong Typhoon Shelter breakwater and seawalls in the former South Apron and Cha Kwo Ling (CKL) areas, where they are located directly above or in close proximity to the TBM launching shaft or along the tunnel alignment. The GNSS receivers installed at these sensitive receivers can be located as a unique point on Earth by using trilateration technique. With the addition of the Chinese BeiDou Satellite System and advancements in computing algorithms, improved accuracy and reliability for precise positioning of the GNSS receivers can be achieved, with an accuracy of one to two millimetres, which is on a par with conventional surveying methods.

In addition, the remote sensing technique of InSAR was employed for mapping ground deformation, using satellite radar images acquired for every 11 days of a satellite's orbiting cycle, at the CKL Village where the closely annexed houses and narrow alleys in the village rendered conventional survey

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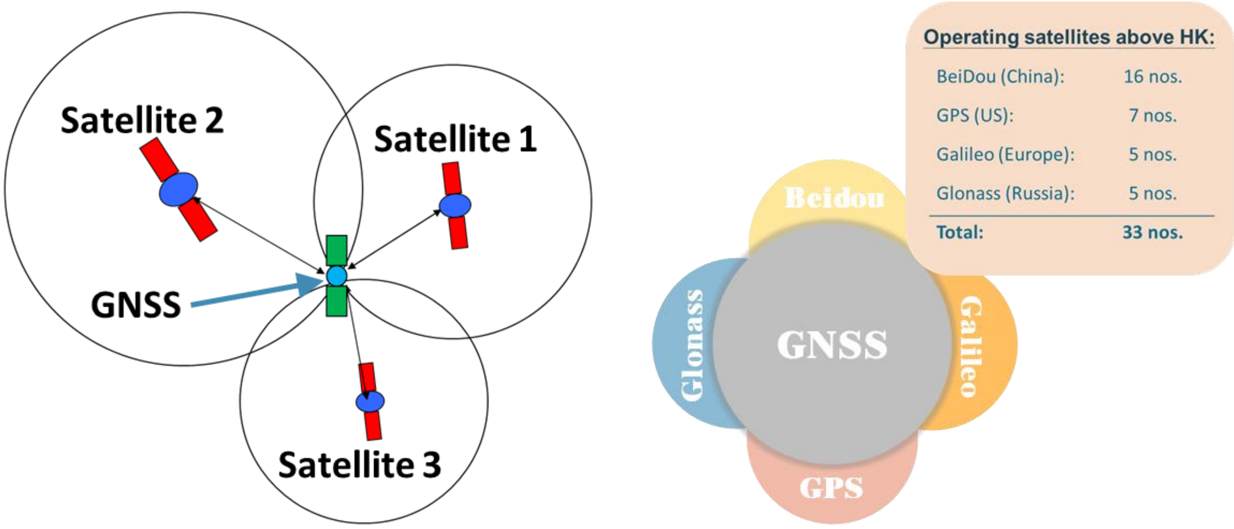
monitoring extremely difficult and time consuming. The InSAR technique identifies ground deformation based on the phase differences between high-resolution satellite radar images taken when the radar satellite revisits the exact same location. Compared with GNSS, the InSAR technique does not require any pre-installed receiver or power supply on the ground surface making it extremely suitable for deformation monitoring of areas with restricted access. Details of the site application of these two techniques are presented in the following sections.

2 Global Navigation Satellite System (GNSS) Monitoring

2.1 Working Principle

GNSS rover stations installed on the ground surface can continuously and automatically receive microwave signals emitted from the operating satellites travelling above Hong Kong for which the signals carry positioning and timing data, and record the time taken for the signals emitted from each satellite in space to calculate the distance from the satellite. With the use of GNSS base stations, the accuracy and precision of the system can be further enhanced.

In principle, a minimum of 3 nos. of satellite is sufficient to determine the position (i.e. x, y, z-coordinates in 3-dimensional space) of the GNSS rover station on the Earth's surface by trilateration algorithm (as illustrated in Figure 1 below). However, by employing all available satellite systems orbiting above Hong Kong, including Beidou (China), GPS (US), Galileo (Europe) and Glonass (Russia), a total of up to 33 nos. of satellite can be adopted by the GNSS system for precise positioning with an accuracy of ± 1 to 2 mm, which is practically on a par with the conventional survey system.



(a) (b)

Figure 1: (*a) Locating GNSS rover stations on Earth by trilateration with minimum 3 nos. of satellite and (b) Operating satellites above Hong Kong for GNSS monitoring*

All real-time data collected at the GNSS rover stations is relayed to the cloud server in Hong Kong via 5G mobile network, where data processing will take place in the server using the proprietary computing algorithm. The output movement monitoring data will then be posted to the dedicated web portal via internet, from which the real-time movement monitoring data can be viewed graphically in the web portal.

2.2 Field Installation and Monitoring

In T2 project, the GNSS monitoring was implemented in two phases. The phase 1 GNSS rover stations were installed at the rooftop of the PWCL Building and along the South Apron seawall to monitor the induced movement due to the bulk excavation of the adjacent TBM launching shaft and due to the TBM crossing underneath the South Apron seawall respectively. As for phase 2, the GNSS rover stations were installed on Kwun Tong Typhoon Shelter breakwater and along CKL seawall to monitor the induced movement due to TBM crossing underneath the breakwater and CKL seawall. The two-phase installation is illustrated in Figures 2 and 3 below.

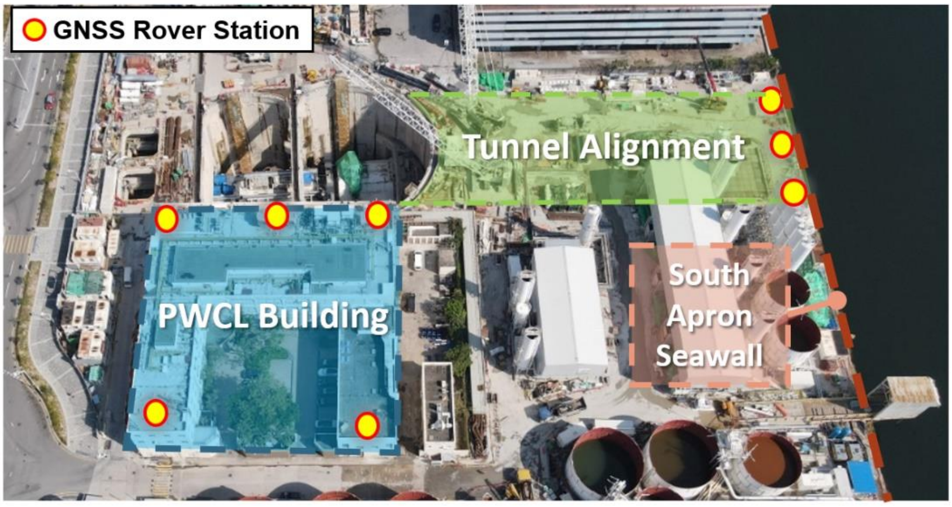


Figure 2: *Phase 1 GNSS monitoring: at rooftop of PWCL Building (left) and along South Apron seawall (top right)*

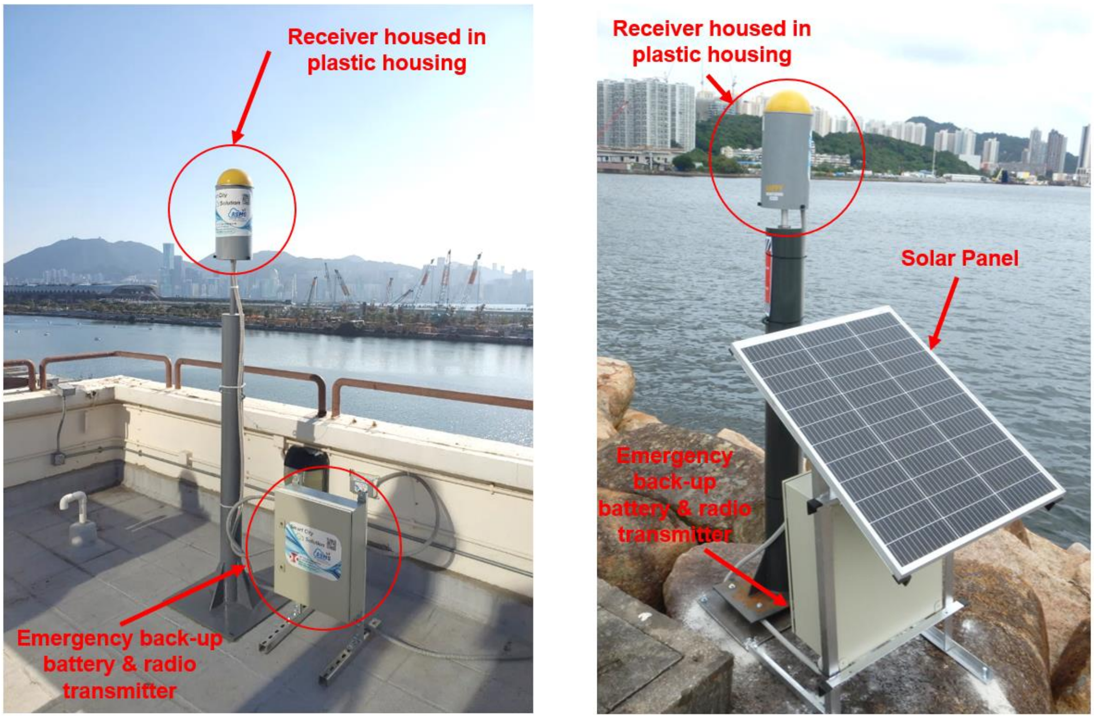
(a) (b)

Figure 3: (*a) Phase 2 GNSS monitoring: at Kwun Tong Typhoon Shelter breakwater and (b) along Cha Kwo Ling seawall*

Construction of the TBM launching shaft is the critical element in this project, with specific considerations to its deep excavation works (38 m depth) and close proximity – only 2.5 m from the existing foundations of the PWCL Building, which is a sensitive structure in which the laboratory equipment is sensitive to vibration and the government's public laboratory testing services must be maintained and uninterrupted during the construction of the TBM launching shaft and the subsequent launching of both TBMs. Hence, stringent monitoring requirements are imposed on the PWCL Building. Apart from conventional manual survey, GNSS is also adopted to supplement the monitoring of building movement of the PWCL Building during the works period.

The typical set-up of GNSS rover stations at the PWCL Building is shown in Figure 4(a) below. A minimum of 70% sky visibility is recommended by the GNSS service provider to ensure that sufficient satellite signals are received to produce reliable monitoring data and this requirement is achievable at the rooftop of the PWCL Building.

As for the Kwun Tong Typhoon Shelter breakwater, it is an isolated breakwater surrounded by sea and without an electrical power supply, each GNSS rover station installed on the breakwater was equipped with a solar panel to provide electrical power to the receiver of the rover station, as shown in Figure 4(b).

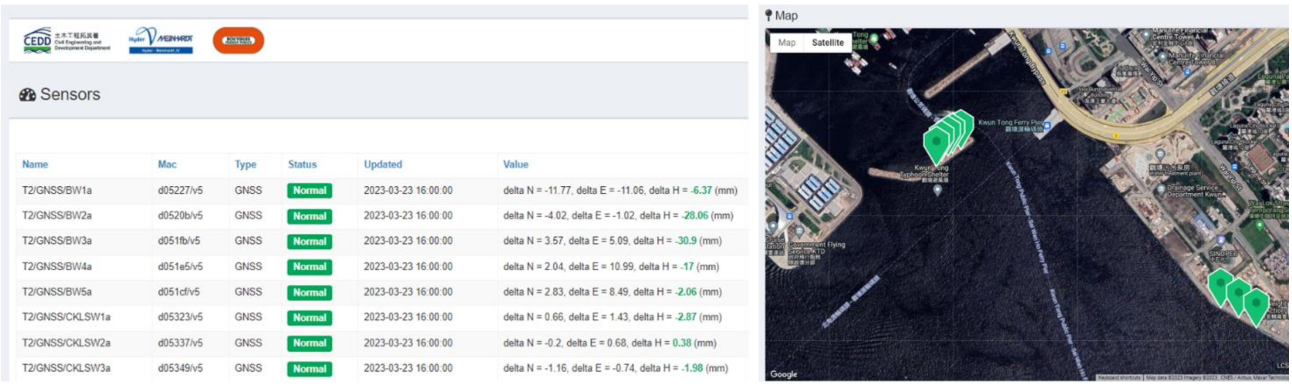


(a) (b)

Figure 4: *(a) Typical setup of GNSS rover station at rooftop of PWCL Building and (b) at Kwun Tong Typhoon Shelter breakwater with solar panel*

2.3 Monitoring Results

All real-time GNSS monitoring data can be viewed via the dedicated web portal, as indicated in Figure 5 below.



(a) (b)

Figure 5: *(a) Dedicated web portal for real-time reporting of monitoring data and (b) Location plan of rover stations at Kwun Tong Typhoon Shelter breakwater and Cha Kwo Ling seawall as view in web portal*

In this paper, the GNSS settlement monitoring data collected at the PWCL Building and the South Apron seawall in phase 1 monitoring were compared with those settlement data surveyed by conventional methods, viz a survey marker on the rover station at the PWCL Building and ground settlement markers along the South Apron seawall.

For the PWCL Building, GNSS monitoring covered the whole works period of bulk excavation at the TBM launching shaft which is located at only 2.5m away from the piles of the PWCL Building, and the works period of the subsequent base slab construction and assembly of the two TBMs. Based on the monitoring results for the GNSS rover station located at the northeast of the building (see Figure 6), it is shown that the settlement monitoring records were generally consistent for those taken by GNSS and manual survey.

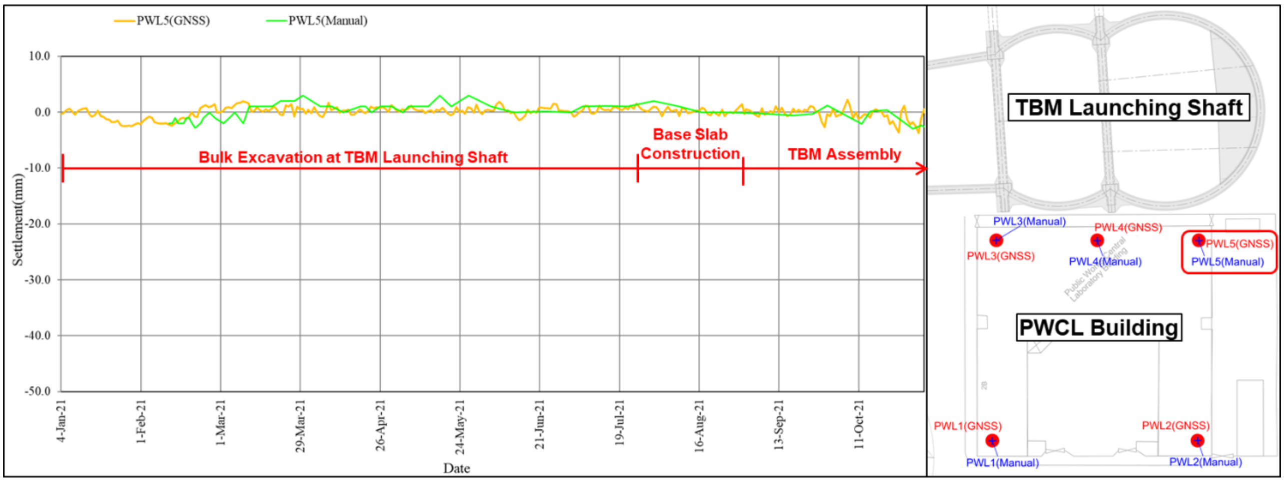


Figure 6: *Comparison of settlement monitoring data by GNSS and manual survey at rooftop of PWCL Building*

For the South Apron seawall, GNSS monitoring covered the period of TBM crossing underneath the seawall for the excavation of the Westbound Tunnel. According to the monitoring results for the GNSS rover station located at the seawall coping (see Figure 7), it is shown that the ground settlement monitoring records were in good consistence for those taken by GNSS and manual survey.

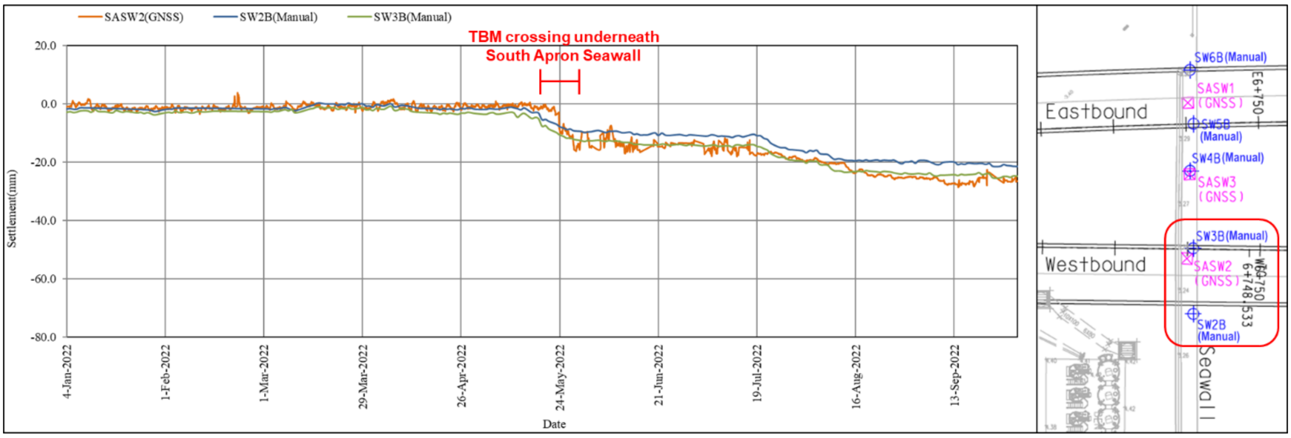


Figure 7: *Comparison of ground settlement monitoring data by GNSS and manual survey at South Apron Seawall*

Based on the above results, it is observed that a similar trend of settlement was demonstrated by both GNSS and manual survey at the PWCL Building and the South Apron seawall. Hence, it is considered that GNSS monitoring can effectively supplement the conventional survey monitoring, for close monitoring of sensitive / important structures during critical construction periods.

2.4 Merits and Limitations

For the merits, the GNSS technique can provide continuous monitoring readings at 15-minute intervals over a 24-hour/7-day continuous period, which is far more frequently than the commonly adopted daily monitoring using conventional surveying methods, hence it is an ideal monitoring method for sensitive / important structures requiring close monitoring during critical construction periods. Additionally, GNSS monitoring is not affected by adverse weather conditions. With respect to eco-friendly efficiency, the GNSS rover stations can be powered by solar panels, which is advantageous for monitoring in areas with difficult and/or remote access, such as the sea-locked Kwun Tong Typhoon Shelter breakwater.

As for limitations, when installing GNSS rover stations in the urban area, the engineers should pay attention to the presence of the adjacent buildings with glass curtain walls, which will create multipath signals and may cause errors in the GNSS monitoring data. Also, 70% of sky visibility is required for the GNSS rover station to receive sufficient satellite signals to produce reliable monitoring data, so the rover stations should not be installed near objects which may cause sky invisibility, such as near the wall of buildings or under trees or other vegetation.

By knowing the merits and limitations of the GNSS technique, engineers can make the best use of this technique to facilitate monitoring of sensitive / important structures or remote areas with difficult access.

2.5 Site Consideration for Cha Kwo Ling Village

The T2 project team has considered to extend the use of GNSS monitoring to the settlement monitoring of the existing structures in CKL Village. However, the GNSS rover stations require a flat and firm surface for installation and the corrugated rooftop of the existing village houses do not provide suitable locations to install the rover stations, as shown in Figure 8 below. Therefore, the InSAR technique was adopted as an alternative for settlement monitoring in CKL Village.

(a) (b)

Figure 8: *(a) Corrugated rooftop unsuitable for installation of GNSS rover station in CKL Village and (b) Rooftop occupied by antennas & prior consent from resident required for installing GNSS rover station*

3 Interferometric Synthetic Aperture Radar (InSAR) Monitoring

3.1 Working Principle

In T2 project, the InSAR monitoring data was based on the satellite images provided by the TerraSAR-X satellite, which is a commercial German Synthetic Aperture Radar (SAR) Earth observation satellite launched in 2007 with operation altitude at 514 km above the ground surface, as shown in Figure 9 below.

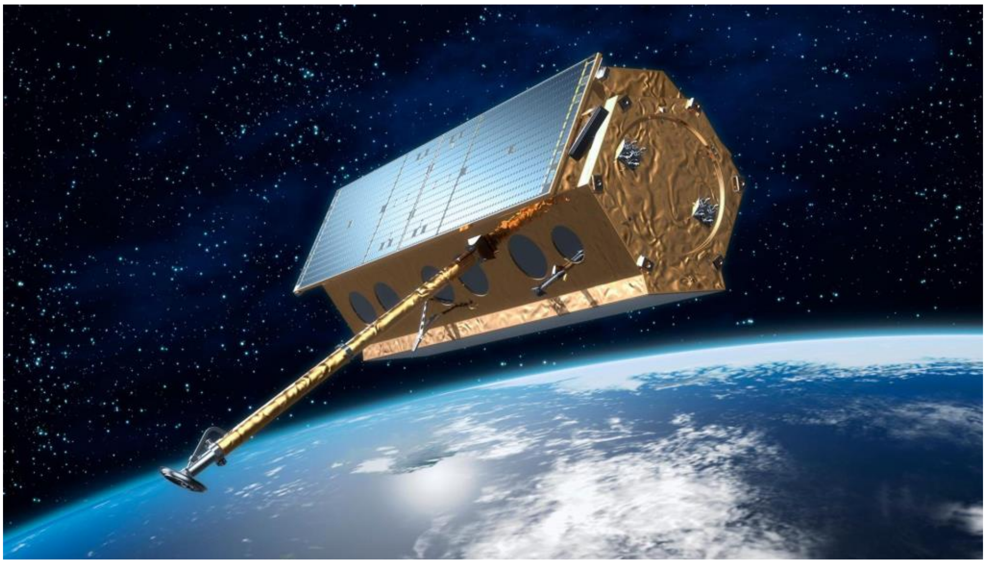


Figure 9: *Computer image of TerraSAR-X satellite with X-band radar antenna (bottom left)*

(Source of image: German Aerospace Center (www.dlr.de))

The X-band radar emitted by the satellite to the ground surface, with typical frequency of 9.65 GHz and wavelength of 3.1 cm within the electromagnetic spectrum of microwave, can achieve higher sensitivity in detecting small change on the ground surface when the radar signal is reflected back to the satellite. Hence, the X-band radar is commonly adopted for creating high resolution satellite images for terrestrial movement measurement purposes. The satellite makes an orbit around the Earth with a repeat period of 11 days and therefore the satellite images taken at the same location on Earth will have an interval of 11 days.

Measurement of ground deformation is made possible by measuring the phase difference of two radar images taken 11 days apart when the satellite revisits the exact same location. By detecting the phase difference using the latest radar technology to form interferogram, the ground deformation (i.e. the change in ground level) can be measured accurately (Löfgren *et al.,* 2008), as illustrated in Figure 10 below.

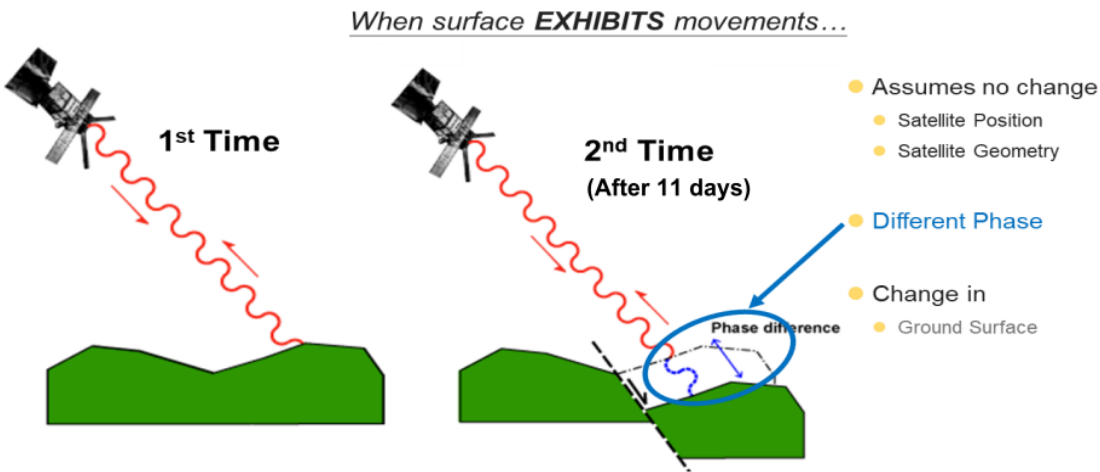


Figure 10: *Measurement of ground movement by measuring phase difference of radar signals emitted at different times (http://comet.nerc.ac.uk/schoolssar_making.html, 2008-09-04)*

Each TerraSAR-X satellite image can cover an area of 30 km x 50 km (width x length) on the ground (see Figure 11), with spatial resolution (i.e. pixel size) of 3 m x 3 m on plan and vertical accuracy of ± 2 mm. For CKL Village, the angle of incidence (□) of the acquired satellite images is 37°, with descending satellite orbit over the Hong Kong's sky.

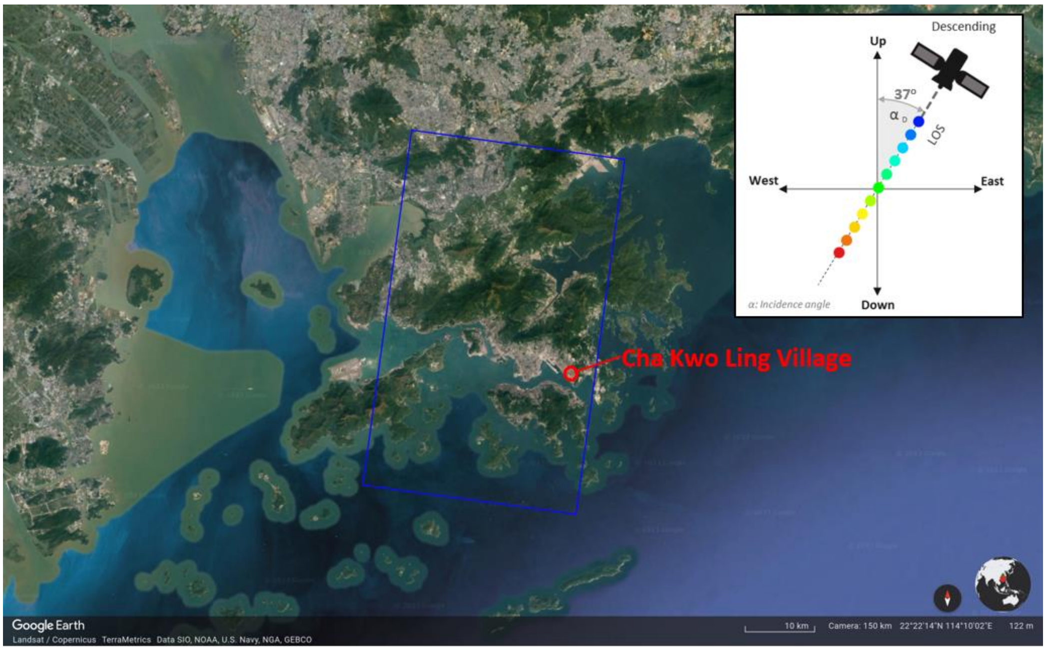


Figure 11: *Coverage of one TerraSAR-X satellite image (30 km x 50 km, in blue rectangle) over Hong Kong including the CKL Village*

3.2 Site Coverage by InSAR under T2 Project

In T2 project, there are a total of 840 nos. of InSAR monitoring points in CKL Village, as shown in Figure 12 below. Due to the closely annexed village houses or squatter dwellings with narrow alleys in

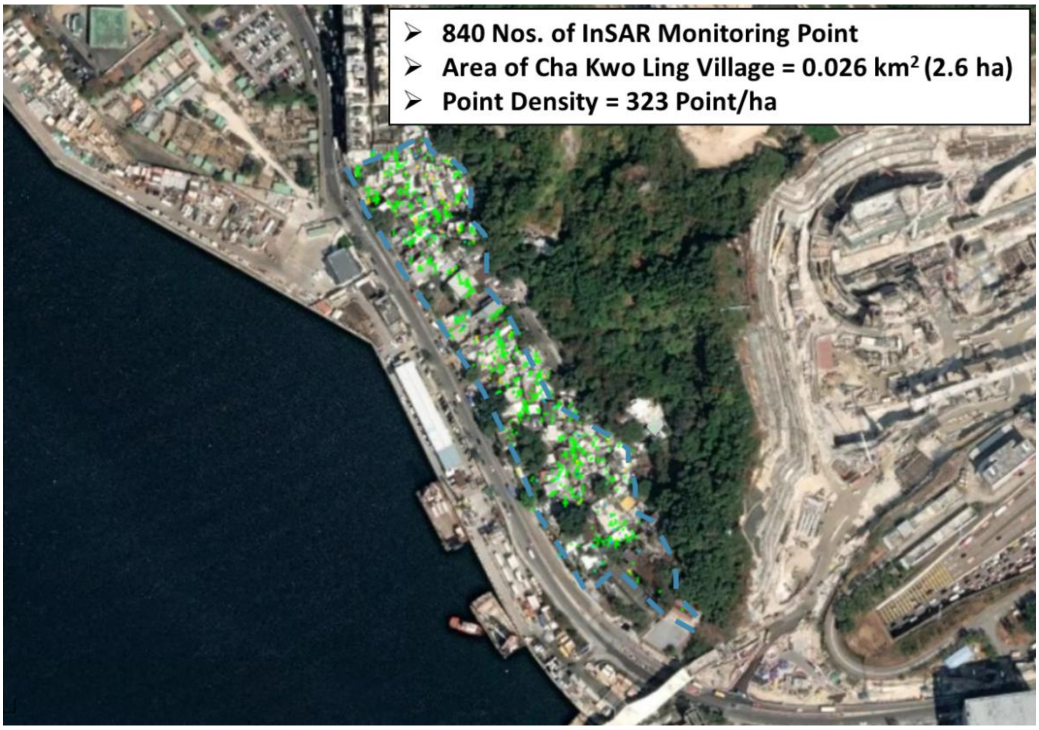


Figure 12: *InSAR monitoring points (green dots) inside CKL Village (bounded by blue dotted line)*

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CKL Village, most of the InSAR monitoring points are located on the roof of the structures which can reflect radar signals to form observable monitoring points under InSAR, whereas a small portion of the monitoring points are located on the ground surface of hard pavement.

Under the InSAR monitoring exercise, the satellite images and the associated ground deformation monitoring data, can be acquired as far back as November 2017, which is approximately three years before the commencement of CKL tunnel works under the T2 project. It means that sufficient historical monitoring records at the concerned works area can be retrieved and studied well before the commencement of works to facilitate the review of monitoring data during the works.

3.3 Monitoring Results

The remote sensing of InSAR technique was used to supplement the monitoring of building settlement of the village houses and ground settlement within the CKL Village during the T2 tunnel works period, in which the drill-and-blast and drill-and-break works for both Eastbound and Westbound tunnels were directly underneath the Village. InSAR monitoring was particularly useful during the period of COVID-19 pandemic, in which there was restricted access to the village houses and dwellings for conventional manual survey, and InSAR could provide monitoring data to allow continuous settlement monitoring of the houses and the surrounding ground.

Like GNSS, the InSAR monitoring data can also be readily accessible for review at any time via a dedicated web portal, as shown in Figure 13 below.

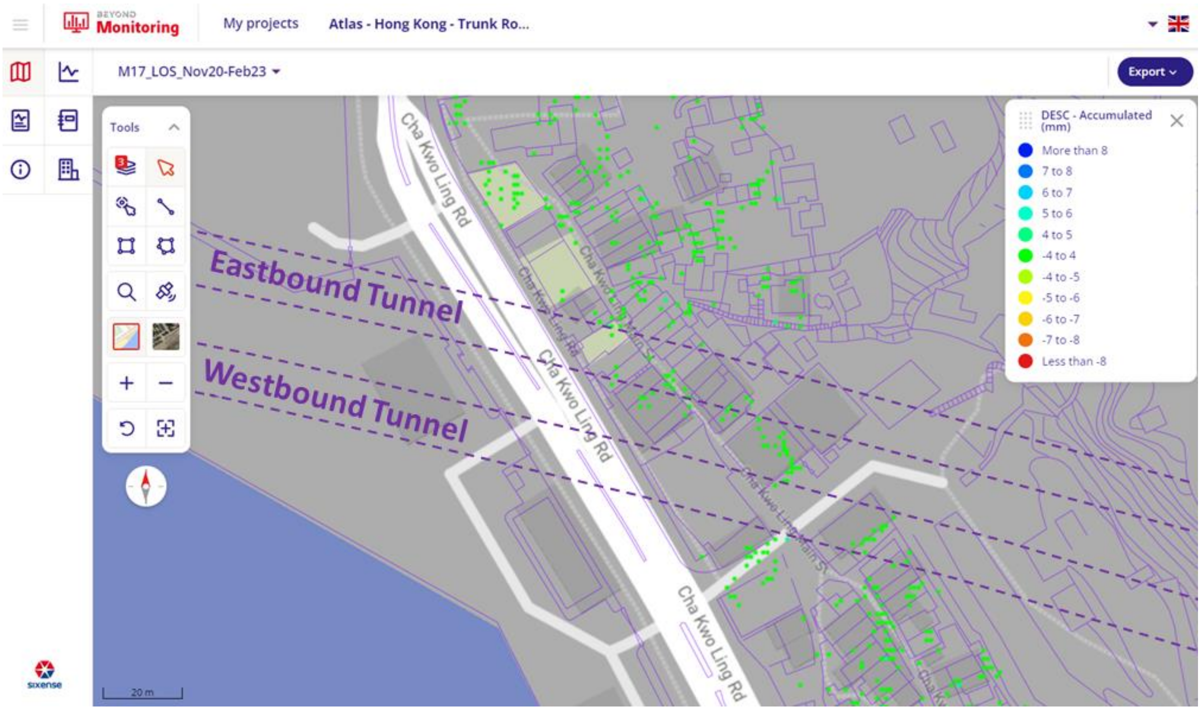

Figure 13: *View of the dedicated web portal of InSAR for monitoring of CKL Village, with green dots representing InSAR monitoring points*

After review of both conventional settlement monitoring data and InSAR monitoring data in the CKL Village during the T2 works period, it is observed that both sets of monitoring data show consistent trends of movement. Therefore, it is considered that InSAR monitoring can be a reliable means of monitoring to supplement conventional manual survey.

3.4 Merits and Limitation

The merits of the InSAR technique include availability of historical monitoring data for review, monitoring unaffected by adverse weather conditions due to the high penetration power of the X-band radar through moisture and no need for installation of any instrument or physical presence of any surveyor, thereby enhancing site safety for the surveying works and making it ideally applicable for monitoring works in inaccessible or remote areas. During the outbreak of COVID-19, any close contact between the surveyors and residents in the narrow alleys of CKL Village could also be eliminated.

As for the limitation, due to the orbiting period of 11 days for the TerraSAR-X satellite, the InSAR monitoring data could only be obtained for every 11 days. However, this limitation can be resolved easily by deploying additional InSAR satellites with different visiting timeframe to Hong Kong, such that the monitoring data can be obtained with closer intervals.

By understanding the above merits and limitation of the InSAR technique, engineers can maximize the use of this technique under the various challenging scenarios of instrumentation monitoring.

4 Conclusions

In the T2 project, both GNSS and InSAR monitoring techniques have been employed very successfully. All monitoring data collected by these techniques was easily accessible through their associated dedicated web portals. Both monitoring techniques are unaffected by adverse weather conditions. In future, it is envisaged that these monitoring techniques will have huge potential for wider geotechnical applications involving movement monitoring in remote and/or restricted areas.

5 Declarations

5.1 Acknowledgements

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