Time Series Satellite InSAR Technique for Disaster Prevention?

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ABSTRACT

Interferometric synthetic aperture radar (InSAR) has been widely used for mapping terrain and monitoring ground deformation. For example, the advanced time series InSAR (TS-InSAR) technique has been increasingly used to measure mm-level urban deformation. Subsidence from underground tunnel excavation has been known for more than a decade in Guangzhou and Foshan in Southern China, but past studies have only monitored the subsidence patterns as far as 2011 using InSAR. In this study, the deformation occurring between 2011 and 2017 has been measured using COSMO-SkyMed (CSK) satellite imagery. We found that significant surface displacement rates occurred in the study area varying from −35 mm/year to 10 mm/year. A detailed analysis has been conducted on several subsidence hotspots along subway lines, especially the sinkhole collapsed in early 2018, suggesting that surface loading may be a controlling factor of the subsidence, especially along the road and highway. Continuous monitoring of the deforming areas is important in order to minimise the risk of land subsidence and prevention of disasters. Satellite InSAR is a powerful and cost-effective technique to strategically guide field survey and in-situ geotechnical monitoring which are labor-intensive and costly. With the accelerated deployment of SAR constellations in recent and future years, it is anticipated that high resolution SAR imagery will be collected more frequently and made available in a more timely manner. As a result, InSAR techniques will play a central role in disaster prevention.

Keywords

InSAR, Foshan, Guangzhou, CSK, subsidence.

INTRODUCTION

Many large deltas in the world have been experiencing land subsidence because of the rapid growth in population and economy (Syvitski et al., 2009; Bakr, 2015). These deltas accommodate a significant percentage of the human population, hence land subsidence in these deltas can lead to serious problems, for example, cracking the buildings and infrastructures, destructing local groundwater systems, generating tension cracks on land and reactivating faults. Moreover, the low-lying nature of the deltas means that the land subsidence can significantly amplify the risk of flood hazards and saltwater intrusion. Therefore, accurate land subsidence data for the major cities in these deltas are crucial to assess the risk of induced land subsidence.

The Greater Pearl River Delta (GPRD) is one of the main hubs for China's economic growth; it is also one of the largest urban agglomerations and fastest urbanisation region in alluvial and lacustrine deposits of the world. In this study, the land stability of Guangzhou and Foshan, two of the main municipalities in GPRD that are located next to each other, is investigated. The studied area was cities of canals on the Pearl River flood plain, where the modern cities are built over the top of the old canals. Majority of the multitrillion-dollar developments in the study area are less than a metre above sea level (area with white colour in Figure 1). Land subsidence in Guangzhou and Foshan has been known for many years, mainly caused by vulnerable geological conditions together with sediment loading and compaction, groundwater extraction and concentrated urban development (Wang et al., 2012; Zhao et al., 2009; Wang et al., 2017). For example, tens of buildings in Jinshazhou at Guangzhou were seriously damaged by local ground subsidence induced by the high-speed railway underground project, resulting in an economic loss of 30 million RMB (or Chinese yuan) (Chen et al., 2012).As another example, a massive sinkhole measured 30 metres wide and five to six metres deep swallowed an eight-lane road on 7 February 2018, where a subway station (GF Line 2) was under construction near the intersection of Jihua Xi road and Foshan No.1 Ring Road Bridge in the middle of Foshan, a city of seven million people. This incident has lead to a total of 11 deaths (hereafter referred to as the 2018 Foshan Accident). In addition, the development in these areas is much faster than its drainage infrastructure could catch up. Together with continually increasing sea level and large land subsidence, the affected population are put under a greater risk of environmental problems, such as flooding and saltwater intrusion. In recent years, Guangzhou has frequently suffered from urban flooding. For instance, on 7 May 2010 and 31 March 2014, extreme rainfall events inundated many streets, leading to severe transport chaos (Huang et al., 2018). The frequent flooding and ground collapse events in Guangzhou have caused huge economic losses and endangered the lives of citizens (Lyu et al., 2016; Zhao et al., 2009; Chen et al., 2012). Analysis of the contributing factors and investigation of the land subsidence in Guangzhou and its neighbor, Foshan, are therefore required for the purpose of subsidence management and disaster prevention.

The time-series radar interferometry (TS-InSAR) technique has been well-known for mapping land deformation in regional scale for many years. TS-InSAR exploits a stack of more than 20 SAR images collected over the same area of interest through a period of time in order to minimize errors and achieve high accuracy in the measurements. TS-InSAR is capable for deriving accurate deformation data with large spatial extent and high spatial resolution that are much more cost-effective compared to the conventional ground-based surveying techniques (Du et al., 2017; Ng et al., 2015; Ge et al., 2014; Perissin et al., 2012; Ng et al., 2012; Chen et al., 2013).

Land subsidence issues in Guangzhou between 2006 and 2011 have been well studied using TS-InSAR techniques. Zhao et al. (2008) utilised 10 C-band ENVISAT ASAR data acquired between 2007 and 2008 to measure the ground subsidence in Guangzhou, and showed that the maximum subsidence rate were -26 to -20 mm/year. Zhao et al. (2008) suggested that the subsidence can be caused by fragile hydrogeological conditions and underground engineering projects. Chen et al. (2012) analysed the ENVISAT ASAR data acquired between 2006 and 2010 and pointed out that anthropogenic activities should be primarily responsible for the local subsidence based on the TS-InSAR result, despite the effect of river system distribution and quaternary sediment, which account for about -15 to 15 mm/year. Wang et al. (2017) cross-validated the TS-InSAR results derived from the ENVISAT ASAR and L-band ALOS PALSAR data acquired between 2007 and 2011 and studied the tunnelling parameters over the metro lines in Guangzhou. Wang et al. (2017) found that the newly excavated tunnels (Lines Two, Three, Six and GuangFo) have local subsidence with an average rate of more than -8 mm/year during this period. They suggested that the maximum settlement for the GuangFo line has increased from -5.2mm to -23.6 mm and its ground loss ratio ranged from 1.5-8.7% between 2008 and 2011. These subsidence studies have provided useful information to improve subsidence management and urban planning in Guangzhou. However, these studies only investigated the land subsidence in the period between 2006 and 2011. Foshan and Guangzhou have a total of 10 metro lines covering a total length of 309 km and 167 stations as of August 2017, most of which have been significant developments in the subway system in Foshan and Guangzhou since 2011. Hence, it is important to understand if these subsidence incidents continue and if any new land subsidence event occurs after the year of 2011. This study aims to fill in this gap by investigating the land deformation in Guangzhou and Foshan occurred between 2011 and 2017 using the X-band COSMO-SkyMed (CSK) SAR data.

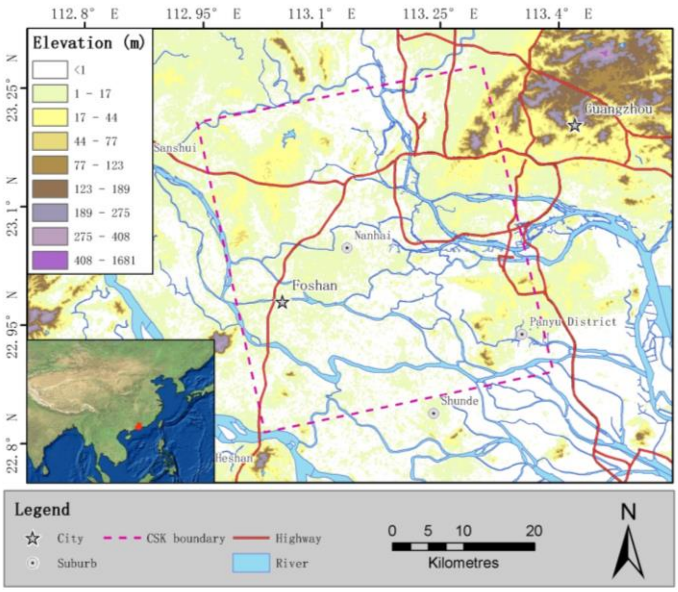


Figure 1. The white area indicates the ground with elevation lower than 1 m (expected flood-prone area).

2. METHODOLOGY

In this study, TS-InSAR analysis is conducted in order to derive the deformation times-series data from the multi-temporal CSK SAR data. The X-band CSK sensors are well known for their high spatial resolution, comparing it to C- and L-band counterparts, such as ENVISAT ASAR and ALOS PALSAR. This advantage allows CSK sensors to be used for generating high resolution displacement map (Perissin et al. 2012). When studying the stability of the transport infrastructures like highway and subway, the size of these infrastructures are often relatively small in width, and hence high resolution measurements are necessary.

The TS-InSAR software, GEOS-ATSA (Advance Time-Series Analysis), is used to obtain the deformation information for Guangzhou and Foshan (Ng et al., 2015). The single master approach is chosen (Ferretti et al., 2001), with eighty five differential interferograms being generated with respect to the selected master image acquired on 9 June 2013. The differential interferograms are generated using the conventional two-pass differential InSAR method (Massonnet et al., 1993; Ge et al., 2009), where the topographic phase components are removed based on the one arc-second Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Rodriguez et al., 2005).

In this study, eighty-six X-band CSK HIMAGE (stripmap) data collected from 20 May 2011 to 27 January 2017 over the study area are analysed. The X-band CSK SAR data used in this study are obtained from the e-GEOS (a company of the Italian Space Agency and Telespazio). The image acquired on 9 June 2013 is chosen as the master image to minimise perpendicular and temporal baselines during InSAR analysis. The perpendicular baseline and the temporal baseline of all other images are relative to the master image acquired on 9 June 2013. The perpendicular baseline ranged between -1069 m and 1317 m, while the time span of the datasets covered 2079 days (approximately 5.7 years).

3. INSAR RESULT

The line of sight (LoS) displacement rate map generated from the CSK data is shown in Figure . The total number of measurement points obtained from the CSK dataset is 3,772,305. The density of the measurement points is approximately 2441 points/km^2. The LoS displacement rate ranges from -32 mm/year to 9 mm/year. The measurement points are relatively dense (~3800 points/km^2) in the centre part of the map mainly because of the dense urban area. Relatively sparse measurement points (~2150 points/km^2) are obtained at the northern and southern parts of the map, because of vegetation at the non-urban area that leads to strong decorrelation.

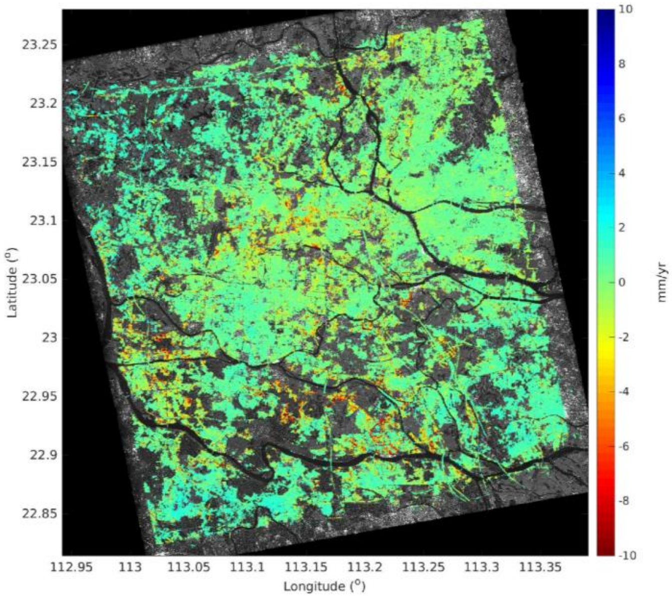


Figure 2. CSK LoS displacmeent rate map (2011 – 2017) for Guangzhou and Foshan overlaid on the average intensity image.

4. INTERPRETATION OF RESULTS AND DISCUSSIONS

Ground subsidence caused by tunnel excavation during subway construction has been well known from 2006 to 2011 (Wang et al., 2017; Ren et al., 2016; Zhao et al., 2009). Since the construction for most of the studied subway lines were already completed by 2010, it is worth understanding whether the subsidence zones identified from those studies still exists after 2011. In addition, during the period from 2011 to 2017, the construction of a number of subway lines have been completed, this includes the Guangzhou (GZ) Line 7, extension of the GuangFo (GF) Line 1 and GZ Line 6. A detailed analysis has been conducted to investigate the land stability along these lines.

In order to investigate the land deformation along the subway lines, the Guangzhou and Foshan subway lines have been overlaid on the displacement rate map. Since most of the subway lines in Guangzhou have already been in operation before 2011, many of the subsidence zones identified in previous studies do not appear in the CSK result, especially for Guangzhou (GZ) Subway Line 1, 5, 8 and APM.

4.1 Subsidence along GZ Line 2 (south part)

For the case of subway GZ Line 2, most already known subsidence zones no longer exist, except the area near Nanzhou and Guangzhou South Railway stations (Figure). According to the news reported in March 2016, cracks of buildings with gaps of approximately 1cm have been found near the Nanzhou station (Luo and Li, 2016). Figure b shows that the land displacement near the reported location (highlighted by the red cross in the figure) is slightly over -5 mm/year. Land displacement of over -10 mm/year has been observed surrounding the Guangzhou South Railway station. Since the centre of the station is relatively stable, it is likely that the land deformation is caused by the development and construction around the station.

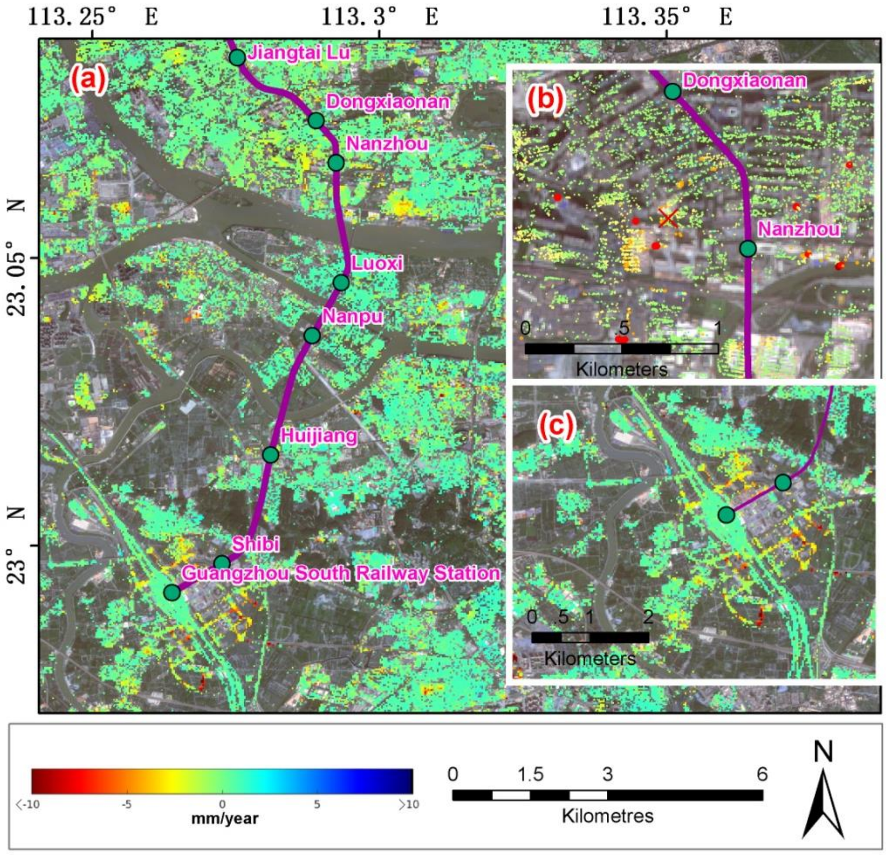


Figure 3. InSAR-measured displacement rate map between 2011 and 2017 over (a) south part of GZ Line 2; (b) Nanzhou station; (c) near Guangzhou South Railway station. The purple line represents the GZ Line 2 and the red cross in (b) represents the location of subsidence incident reported. The background images are the Sentinel-2 true colour images acquired on 1st November 2017.

4.2 Subsidence along GZ Lines 2 (north part), 5, 6 and GF Line 1

Datansha Island is a relatively flat and wide sand bank, which has been well recongised as an active ground subsidence area in related subsidence studies (Wang et al., 2017; Zhao et al., 2009). Because of the unstable geological environments, many hidden Limestone karst caves have developed on this island and consequently many ground collapse accidents have occurred. Both GZ Lines 5 and 6 pass through this island. GZ Line 6 crosses the island in north-south direction underground, while GZ Line 5 crosses the island through the elevated bridge in east-west direction instead of using underground tunnel (Liu, 2006). The south portion of the island, where GZ Lines 5 and 6 intersect, is shown in Figureb. The land deformation pattern observed at Tanwei station in Figureb agrees well with the deformation pattern before 2011 reported in previous studies. Similar observation has also been found in Hesha station for GZ Line 6, with observed deformation rate of over 6 mm/year (Figurec). The deformation found in Jinshazhou is expected to be caused by the over-extraction of groundwater along with construction of the Guangzhou-Wuhan railway project (Miranda, 2010). Another interesting observation is that large deformation with peak deformation rate over 10 mm/year has been found at the Jiaokou (Figureb), i.e. the last station of GZ Line 5. This deformation phenomenon has not been observed in previous studies, suggesting that it is a new deformation zone that occurs after 2011. Since the GZ Line 5 between Jiaokou and Tanwei stations are connected by bridge, the deformation is likely caused by concentrated urban development and heavy loading induced sediment compaction (e.g. cyclic loading of trains).

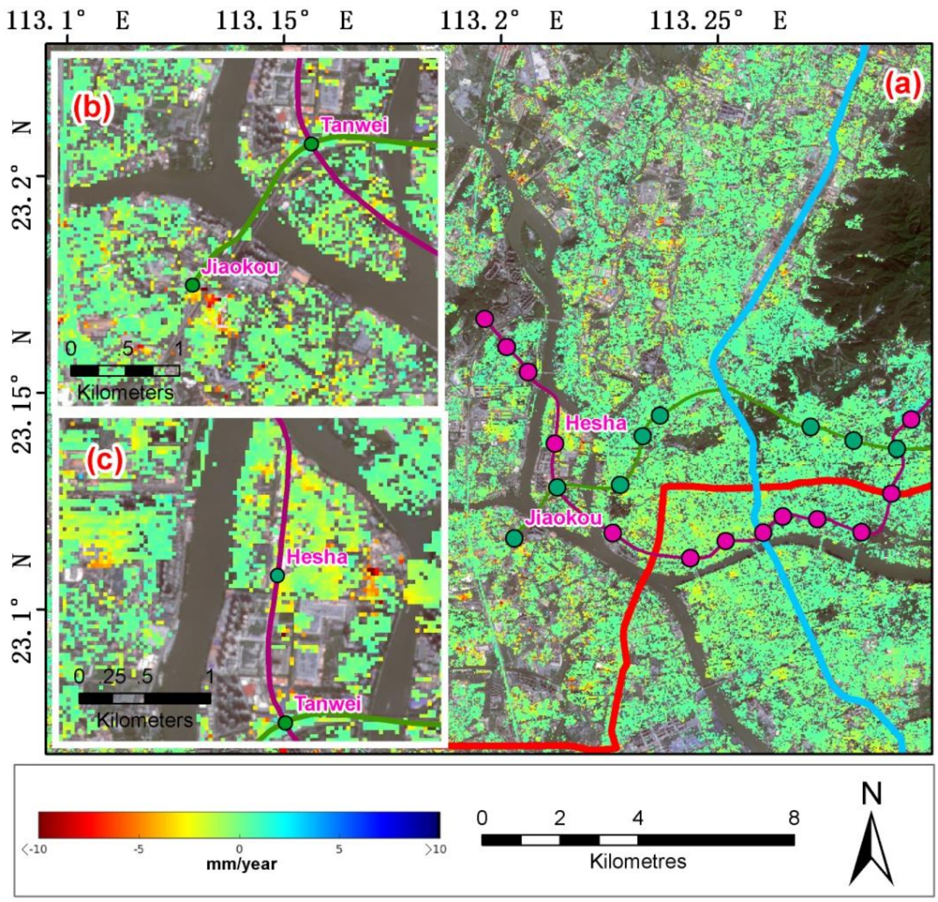


Figure 4. InSAR-measured displacement rate map (2011 - 2017) of (a) GZ Lines 2, 5, 6 and GuangFo (GF) Line 1; (b) Jiaokou and Tanwei stations; (c) Tanwei and Hesha stations. The blue, green and purple lines represent GZ Lines 2 (north part), 5, and 6, respectively. The red line represents the GF Line 1 (east part). The background images are the Sentinel-2 true colour images acquired on 1st November 2017.

4.3 Subsidence along GF Line 1 phase 1 and phase 2

A further investigation has been conducted in the area with varying displacement rate observed between 2011 and 2017. The region of interest is located near the Leigang station along the GuangFo subway line 1 (GF Line 1). The construction works of phase 1 of GF Line 1 began in June 2007 and ended in April 2010. Wang et al. (2017) found that the land subsidence between 2007 and 2011 along the GF Line 1 was concentrated in the section between Kuiqi Lu and Zumiao stations, and middle section between the Financial Hi-tech Zone and Longxi stations, where subsidence in the latter area is worse. According to the CSK result, no obvious land deformation has been found between Kuiqi Lu and Zumiao stations (Figure b). It is possible that the land was settled after 2011. Land surface stablisationhas also been found between Financial Hi-Tech Zone and Leigang stations (Figure c).

Figure 1 shows the deformation time series of a measurement point at the settlement area (point X in Figure). Rapid deformation (over -9.5 mm/yr) is observed until mid 2012, while the ground deformation becomes steady after mid 2012. The underground excavation work for the first stage of GF Line 1 ended in April 2010, suggesting that the settlement duration at this area is roughly 1.8 years. It is also interesting to see the fluctuating displacement, which might be due to soil expansion as a result of rainfall. However, no reduction in land deformation has been observed between Longxi station and Financial Hi-Tech Zone station. The land deformation in this region may be caused by other factors instead of tunnelling, for example, groundwater over-extraction and soil consolidation due to dense high rise building.

The construction work of GF Line 1 extension (phase 2) started in September 2012 and ended in December 2016. No obvious subsidence pattern has been found (Figure) along the GF Line 1 extension except between the Dongping and Xincheng Dong stations (the last two stations). The subsidence at the east of Xincheng Dong station has been known for long time. The land displacement time series for the deformation zones at the west of Xincheng Dong station is shown in Figure . It can be seen that the deformation patterns consisted of 4 stages: (1) the land is stable until mid 2012; (2) rapid land deformation can be seen between late 2012 to early 2013; (3) the land becomes stable again until mid 2014; (4) rapid land deformation occurs again since mid 2014. The displacement time series seems to match with the construction period, hence the deformation observed may be related to the construction work.

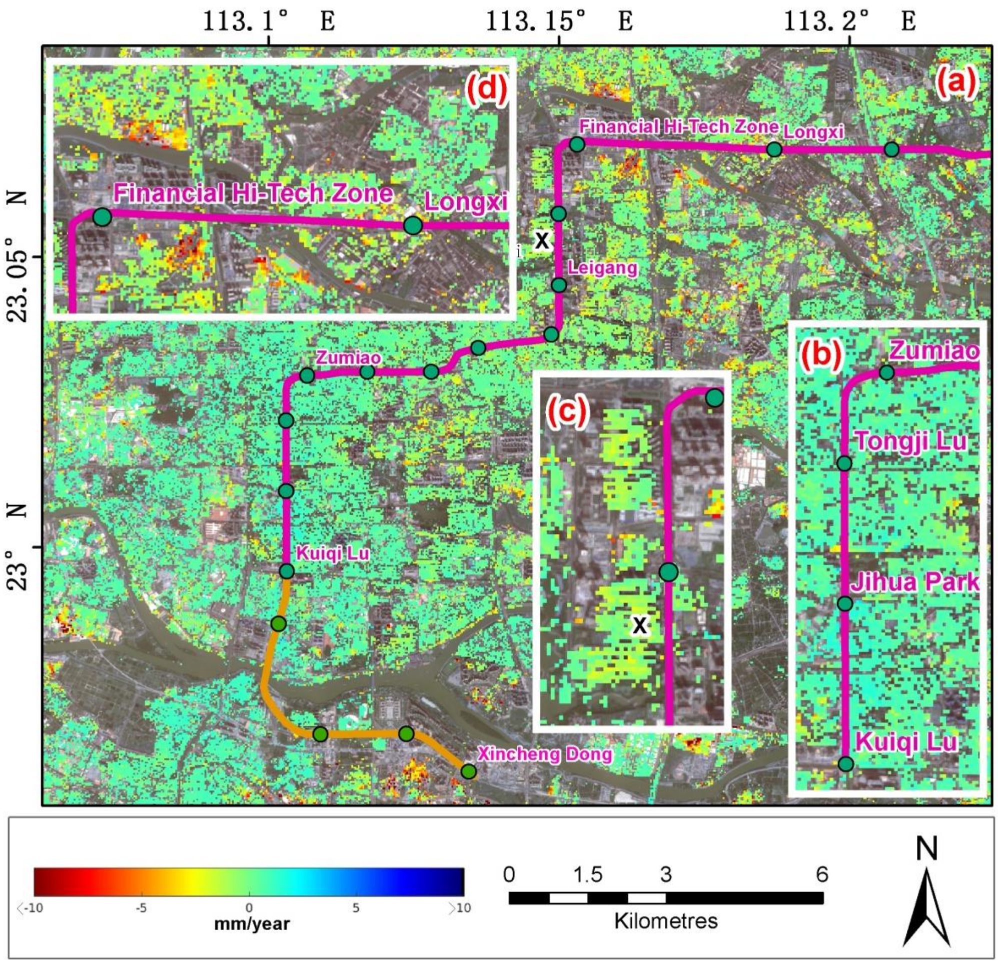


Figure 5. InSAR-measured displacement rate map between 2011 and 2017 over (a) GF Line 1 (west part); (b) section from Zumiao station to Kuiqi Lu station; (c) section from Financial Hi-Tech Zone station to Leigang station; (d) section from Longxi station to Financial Hi-Tech Zone station. The purple line represents the GF Line 1 phase 1 and the orange line represents the GF Line 1 phase 2 (i.e. extension of phase 1). The background images are the Sentinel-2 true colour images acquired on 1st November 2017.

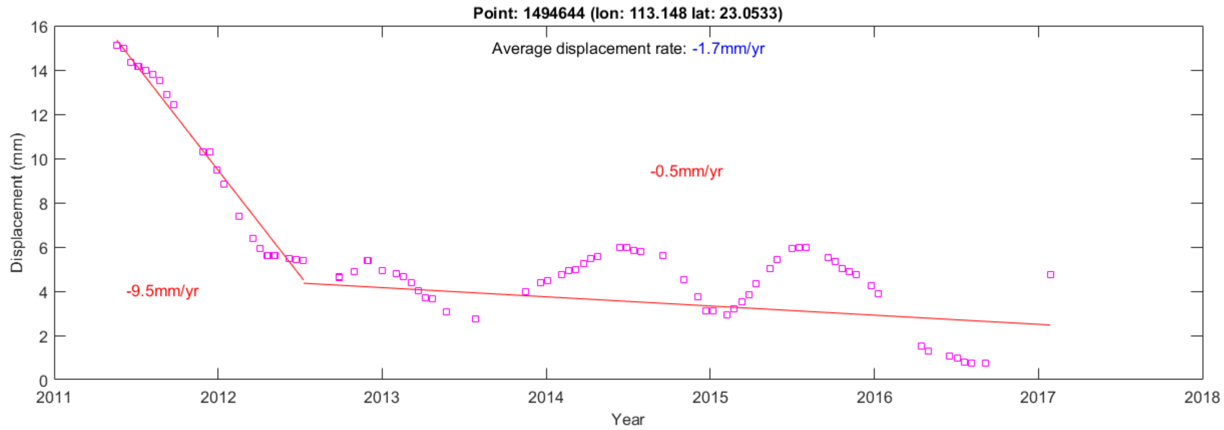


Figure 1. InSAR-measured displacement series in Nanhai district (point X in Figure c).

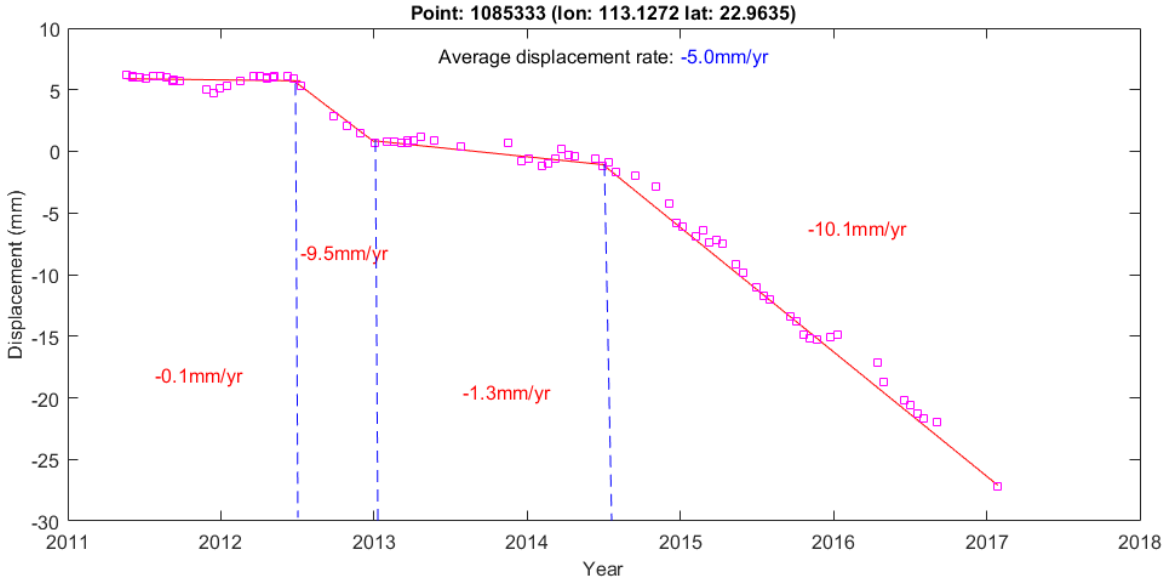


Figure 7. InSAR-measured displacement series near Dongping and Xincheng Dong stations.

4.4 Subsidence along the GZ Line 7, GZ Line 7 extension and GF Line 3

GZ Line 7 is a recently operated subway line with its construction began in April 2013 and ended February 2016. Unfortunately, the CSK acquisitions only cover a portion of the line (i.e. from Nancun Wanbo station to Guangzhou South Railway station). Figure shows the land deformation along the GZ Line 7. As can be seen in Figure, it is very difficult to justify if there is any subway-related land deformation based on the CSK result. Very limited measurement points can be obtained from the CSK dataset, because of the heavy development and construction on the ground surface along the GZ Line 7 at the same time of underground tunnel excavation. A typical example is the Nancun Wanbo station (Figureb). It can be observed that there are some measurement points with deformation up to 10 mm/yr surrounding the station, but there are no measurement points at the centre of the deformation zones (i.e. near the station). This issue is found for most stations along the GZ Line 7.

The two subway lines, GZ Line 7 extension and GF Line 3, which pass through the Beijiao Township are under construction as the manuscript is prepared (construction began in mid to late 2016). Since Beijiao township are well known for rapid land subsidence in Foshan (Wang et al., 2014), it is important to investigate the land stability along the two subway lines. It can be seen in Figurea that the GZ Line 7 extension has passed through a number of deformation zones where some of them are deforming with a rate of over 15 mm/year. A large portion of GF Line 3 is located at the rapidly deforming areas (Beijiao Township). Figurec shows the zoom-in land displacement rate map at the intersection of GZ Line 7 extension and GF Line 3, where large deformation rate of over 15 mm/year has been observed. The sections of two subway lines that follow the National Highway Beijing Zhuhai line (highlighted by white arrow in Figurec) are experiencing rapid deformation.

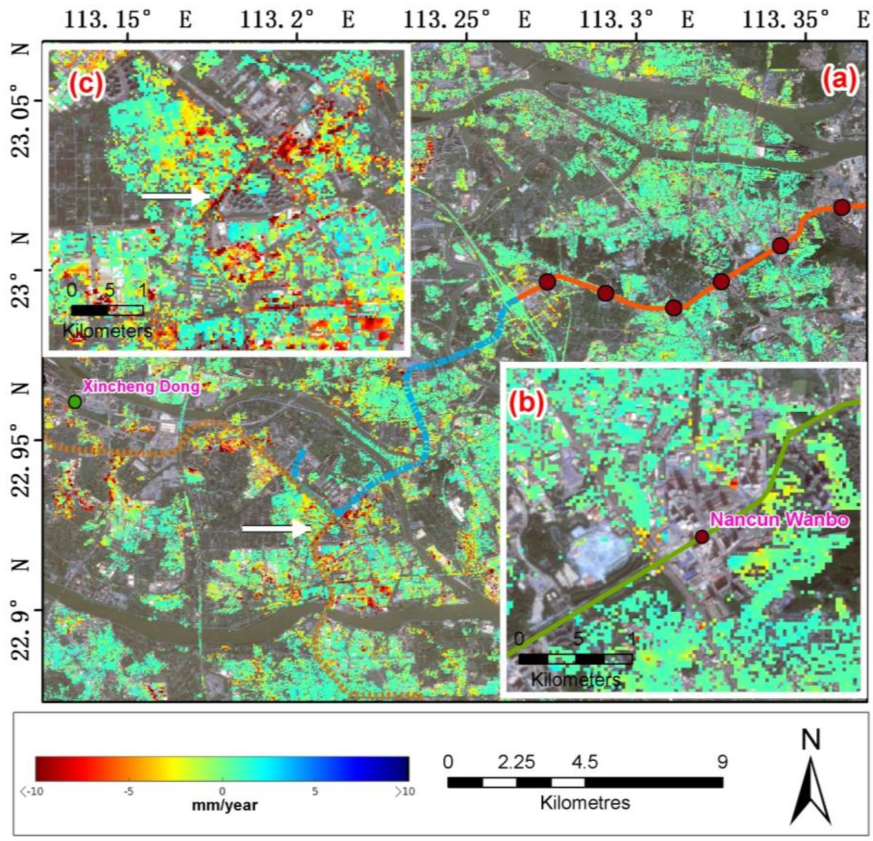


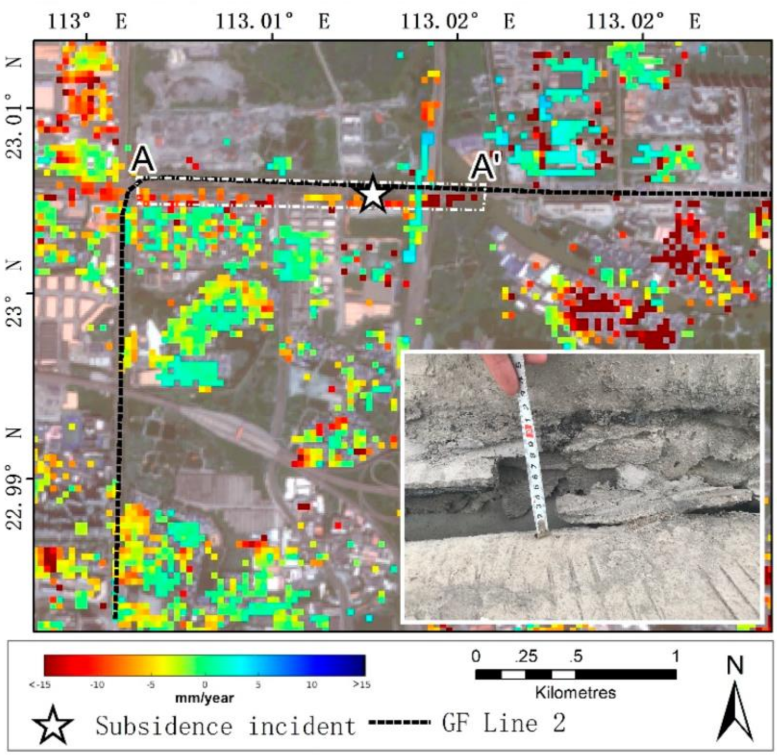
Figure 8. InSAR-measured displacement rate map (2011 – 2017)
(a) GZ Line 7, GZ Line 7 extension (under construction) and GF Line 3 (under construction);
(b) Nancun Wanbo station;
(c) two under construction subway lines.
The orange, blue and brown line represents the GZ Line 7, GZ Line 7 extension and GF Line 3. The background images are the Sentinel-2 true colour images acquired on 1st November 2017.

4.5 The 2018 Foshan Accident

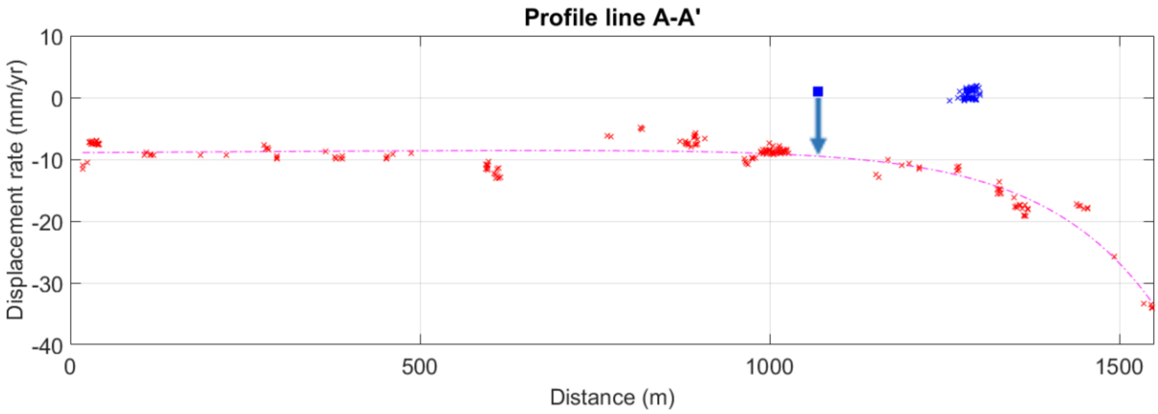
The incidence started with water leaking into the underground tunnel under-construction, which leads to the collapse of the ground. While the water leaking maybe caused by the broken pipe buried underground or the change in groundwater flow paths, they are all caused by ground subsidence. The aerial photo of the sinkhole (Xinhua News Agency 2018) and the displacement rate map near the sinkhole are shown in Figures 9a and 9b, respectively. The exact location of the sink hole is highlight by the white star in Figure 9b. It is observed that the subsidence along the Jihua Xi road (A–A' in Figure 9b) is mostly over -8 mm/year, reaching up to -30 mm/year in some parts (Figure 9c). Subsidence phenomenon has been observed even before the start of subway construction work in June 2014. Based on this observation, surface loading due to heavy trucks on ground surface is expected to be the contributing factor for the subsidence at Jihua Xi road. According to Prassetyo and Gutierrez (2016), surface load in saturated ground can lead to groundwater flow into an underground tunnel.

Therefore, continuous monitoring in this and other similar areas is very important to minimise the risk of ground collapse during or after the underground excavation work. Moreover, the affected areas are located near the industrial and agricultural areas, where groundwater over-extraction is expected. Hence understanding the influence of the spatially uneven subsidence caused by groundwater extraction at the shallow aquifer to the transport systems, and how to deal with the groundwater extraction near the railway/subway lines are interesting topics for future study.

(a) Aerial photo of the sinkhole



(b) InSAR result near the site



(c) Subsidence profile (A–A’) near the sinkhole. The blue square indicates the location of the incident. The red crosses represent the subsidence rate along Jihua Xi road. The blue crosses represent the subsidence rate at the Foshan No. 1 Ring Road Bridge.

Figure 9 The 2018 Foshan Accident and the relevant InSAR result.

5. CONCLUSION

This paper reports the characteristics of land deformation at Guangzhou and Foshan derived from the CSK data acquired between May 2011 and January 2017. A total of 86 CSK data have been analysed using the TS-InSAR analysis technique to explore the evolution of land displacement. The result shows that the displacement rates at these municipalities are between -32 mm/year to 9 mm/year with a standard deviation of 1.6 mm/year.

Although a large spatial scale subsidence phenomenon has not been observed, a few regional scales and many local scale deformation zones have been identified in these municipalities. The main causes of land deformation as a result of human activities are groundwater over-extraction and underground tunnel construction. A number of possible groundwater subsidence zones have been identified mostly in the agricultural and industrial areas. The spatial extent of groundwater subsidence found in Guangzhou and Foshan are relatively small, which is because most groundwater was extracted close to the ground surface.

For the case of underground construction induced land deformation, it is found that many of the subsidence zones identified in the previous studies by other scholars have become stable according to the CSK-derived displacement result. Although a few of the previously identified subsidence zones still exist in the CSK result, most of the underground excavation works in these zones have been completed before 2011 and are unlikely to cause further deformation. It is possible that the deformations are caused by other factors such as groundwater over-extraction and sediment compaction due to building weights.

Analysis has been conducted to investigate new land deformation zones due to subway construction work after 2011. Several new land deformation zones have been identified along the GZ Line 7, extension of the GF Line 1 and GZ Line 6, which have not been identified in previous studies. Most of these zones are found in the Beijiao Township. Moreover, because of the rapid development along the recently constructed subway lines, few InSAR measurement points are available near the stations along these lines. The two under-construction subway lines, GZ Line 7 extension and GF Line 3, have been overlaid on the displacement rate map which shows that these lines actually passed through a number of deformation zones, where deformation rate of over 15 mm/year are observed.

The tragic accident in Foshan highlights the extreme importance of using satellite InSAR as a powerful and cost-effective technique to strategically guide field survey and in-situ geotechnical monitoring which are labor-intensive and costly. In order to prevent disasters during or after the underground construction work, however, further research is needed to inform potential ground collapse with InSAR. Ultimately, it is possible to issue warnings to relevant authorities based on InSAR and follow up with field survey so that remedial action can be undertaken. CSK is the first and only SAR satellite constellation in operation. With the accelerated deployment of SAR constellations in recent and future years, it is anticipated that high resolution SAR imagery will be collected more frequently and made available in a more timely manner. As a result, InSAR techniques will play a central role in disaster prevention.

It must be pointed out that, although our study is very focused towards the specific geographic area of Guangzhou and Foshan, the methodology and interpretation of results would have significant impact and potential for other geographic areas, given the global coverage of satellite SAR missions and similar urban challenges faced by global cities.

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