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Investigating the Structural Health of High-Rise Buildings and Its Influencing Factors Using Sentinel-1 Synthetic Aperture Radar Imagery: A Case Study of the Guangzhou–Foshan Metropolitan Area

Di Huang , Zhixin Qi *, Suya Lin, Yuze Gu , Wenxuan Song and Qianwen Lv

School of Geography and Planning, Sun Yat-sen University, Guangzhou 510006, China

* Correspondence: qizhixin@mail.sysu.edu.cn

Abstract: Urban growth is increasingly shifting from horizontal expansion to vertical development, resulting in skylines dominated by high-rise buildings. The post-construction operations and maintenance of these buildings are critical, requiring regular structural health monitoring (SHM) to proactively identify and address potential safety concerns. Interferometric synthetic aperture radar (InSAR) has proven effective for monitoring building safety, but most studies rely on high-resolution synthetic aperture radar (SAR) images. The high cost and limited coverage of these images restrict their use for large-scale monitoring. Sentinel-1 medium-resolution SAR images, which are freely available and offer broad coverage, make large-scale SHM more feasible. However, studies on the use of Sentinel-1 SAR images for structural health monitoring, especially at large spatial scales, remain limited. To address this gap, in this study, Sentinel-1 SAR images and PS-InSAR technology are proposed for performing a comprehensive structural safety assessment of super high-rise buildings in the Guangzhou–Foshan Metropolitan Area (GFMA) and for analyzing the influencing factors. Our assessment shows that while the overall structural safety of these buildings is satisfactory, certain areas, including Pearl River New Town, central Huadu district in Guangzhou, and southeastern Shunde district in Foshan, exhibit suboptimal safety conditions. We verified these findings using GNSS data and on-site investigations, confirming that Sentinel-1 SAR imagery offers reliable accuracy for monitoring building structural health. Furthermore, we identified factors such as settlement in soft soil layers, the construction of surrounding (underground) infrastructure, and building aging, which could potentially impact building structural safety. The results demonstrate that Sentinel-1 SAR images provide a reliable, rapid, and cost-effective method for the large-scale monitoring of building stability, enhancing our understanding of the underlying mechanisms and informing strategies to prevent potential safety crises, and also ensuring the sustainable development of society.

Keywords: Sentinel-1; structural health monitoring (SHM); Guangzhou–Foshan metropolitan area; PS-InSAR; super high-rise building



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1. Introduction

In today's era of rapid urbanization, cities have increasingly turned to vertical expansion as horizontal development reaches its limits. To optimize land resource utilization, there is a growing demand for upward space. With the backing of financial, material, human, and technological resources provided by economic development, building heights have flourished, and super high-rise buildings soaring hundreds of meters have become iconic features of urban landscapes. As skyscrapers rise, it becomes increasingly imperative to prioritize building safety.

Buildings cannot simply be considered complete once constructed, the subsequent operations and maintenance are important and necessary, requiring regular structural

health monitoring (SHM) [1–3]. SHM employs automated monitoring systems to periodically gather data on building structures and site environments. By analyzing characteristic information such as geometric deformation, the structural health level is assessed to detect any anomalous deformations, and then, maintenance and repair can be arranged in time to ensure the safety and reliability of the building structure [4,5]. Unfortunately, we have learned of some cases of buildings tilting, collapsing, and even casualties. In June 2021, the Champlain Towers condominium in Florida, USA, partially collapsed, causing 98 fatalities. The 40-year-old building had already suffered significant structural damage from saltwater corrosion of the rebar and subsidence but lacked timely maintenance. In September 2023, several buildings in Taipei's Zhongshan district seriously subsided, possibly related to unstable foundations on loose soil and ongoing underground construction nearby. The safety maintenance of super high-rise buildings requires stricter standards, as super high-rise residential buildings accommodate more people per unit area, while prime office buildings generate greater social wealth. Their diverse structures and shapes are also influenced by more loads, complicating the situation. Therefore, regular inspections and assessments of building structural stability and integrity are essential for the early identification of potential structural issues and prevention of tragedies, ensuring responsibility for the safety of occupants' lives and property, and contributing to the sustainable development of society [6]. Monitoring the stability of buildings over large-scale areas and providing alerts for anomalies can assist relevant authorities in focusing on prevention while maintaining an overall perspective, enabling early preparation and reducing losses.

The methods for SHM have been greatly enriched. Traditional geodetic techniques (e.g., leveling and total station) are the most fundamental. With the continuous advances in technology, new techniques such as global navigation satellite system (GNSS), wireless sensor networks [7], and unmanned aerial vehicle (UAV) photogrammetry [8–10] have also been widely applied. However, these methods are more suitable for small-scale monitoring, and large-scale continuous monitoring requires the assistance of satellite remote sensing, such as radar interferometry.

Interferometric synthetic aperture radar (InSAR) technology has been widely used to measure land subsidence [11,12]. The large-scale and millimeter-level displacement precision [12–15] make it stand out from traditional geodetic techniques. With the advantages of being unaffected by weather and stable observation frequency, many scholars have begun to explore the potential of multi-temporal InSAR (MTInSAR) technology in SHM [16–20]. MTInSAR offers unique advantages for building deformation measurement, including long-term, large-scale, efficient, low fieldwork costs, non-destructive monitoring, and the elimination of the need for fixed reference points, thereby overcoming the limitations of traditional methods like leveling [21]. Monitoring super high-rise buildings sometimes involves dangerous high-altitude work, suggesting the need for new alternative methods. The accuracy of the persistent scatterer (PS) InSAR (PS-InSAR) technique in the monitoring of building deformation has been demonstrated as meeting the standard requirements [18,22]. Peduto et al. [19] performed a multi-scale analysis of settlement-induced building damage using the PS-InSAR. Taking the highest building in Wuhan as a case study, the feasibility of PS-InSAR technology in the structural assessment of super high-rise buildings has been affirmed by Li et al. [23]. Most studies have used high-resolution synthetic aperture radar (SAR) images such as COSMO-SkyMed (CSK) [20,24] and TerraSAR-X (TSX) [25,26]. High-resolution SAR images usually require payment and cover a relatively small area per image, resulting in high overall costs, especially for large-scale monitoring. In contrast, medium-resolution SAR images such as Sentinel-1 images are freely accessible, offering more researchers the possibility of conducting related studies. The larger imaging spatial coverage also makes large-scale structural health monitoring (SHM) feasible. However, some researchers may argue that medium-resolution images lack sufficient accuracy, which is why there is still a limited number of studies on their use for building structural monitoring, particularly at large spatial scales. In fact, Zhou et al. [27] compared the accuracy of Sentinel-1A and CSK images using the PS-InSAR for bridge deformation detection and

concluded that the detection accuracy of both was comparable, despite the relatively lower spatial resolution of Sentinel-1A images. Dai et al. [28] used Sentinel-1 images to conduct stability analysis during the reservoir filling period of a dam. Calò et al. [9] assessed the impact of landslides on structures and infrastructures using the high temporal resolution of Sentinel-1 and the high spatial resolution of CSK. These all reflect, to some extent, the potential of Sentinel-1 for structural health monitoring of buildings.

In this study, we present a non-destructive integrated method based on PS-InSAR technology for the monitoring of super high-rise building structural health using Sentinel-1 SAR images. Taking the super high-rise building in the Guangzhou–Foshan Metropolitan Area (GFMA) as a case study, the distribution characteristics of super high-rise buildings are analyzed first. Then, the structural safety assessment of these buildings is conducted, coupled with detailed analyses of buildings in anomalous safety conditions to explore the factors affecting structural health.

2. Study Area and Datasets

2.1. Study Area

Guangzhou and Foshan, two highly urbanized megacities in Guangdong, China, are selected as the study areas (Figure 1a,b). They are geographically adjacent and both located in the core area of the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) in South China, featuring close socio-economic ties and cultural similarities. The “Guangzhou–Foshan Metropolitan Area (GFMA)” proposal was kicked off by the twin city governments in 2000 to promote social and economic integration.



Figure 1. (a,b) location of the study area; (c) three-dimensional view of buildings in part of the study area based on 3D-GloBFP.

A large amount of infrastructure facilities have been completed in the GFMA, with high-rise or high-density buildings that impose heavy loads above ground and an extensive network of metro systems below. Since the completion of the first building over 100 m high in China, the Baiyun Hotel, in 1976, Guangzhou now built nearly 200 buildings exceeding 150 m, while Foshan has over 30 such structures [29], and even more buildings over 100 m

in height. These buildings serve as landmarks, commercial centers, or homes for many and so on, becoming an essential part of daily life.

However, the geological conditions of the GFMA are less than ideal, raising concerns about the long-term durability of these super high-rise structures. The southern alluvial plain is the Pearl River Delta, where Quaternary loose sediments are widely distributed and soft soil develops. Buried karst exists in the northern Guangzhou–Huadu basin. Both of these geological formations are prone to ground subsidence and collapse, posing a threat to the stability of the surrounding buildings. Meanwhile, the high annual precipitation brought by the subtropical monsoon climate and the concentrated rainfall during the rainy season [30] disrupt the stable state of the underground water table, thus affecting land deformation and accelerating the dissolution of karst rocks.

2.2. Study Datasets

2.2.1. SAR Data

A total of 38 ascending Sentinel-1A Synthetic Aperture Radar (SAR) C-band images covering the study area acquired from March 2017 to March 2022 were used to monitor time-series land deformation. We selected the single look complex (SLC) datasets in interferometric wide swath (IW) mode with VV polarization. These SAR images achieve a spatial resolution of 5 m in range and 20 m in azimuth, with an average incidence angle of 39.7° on Track 11.

The Copernicus Sentinel-1 mission is designed as a C-band two-satellite constellation. Sentinel-1A was launched in 2014 and is still operational, while Sentinel-1B was launched in 2016 but retired in 2022, to be replaced by Sentinel-1C. Sentinel-1 operates in a near-polar, sun-synchronous orbit, with a repeat cycle of 12 days for a single satellite, which can be shortened to 6 days when both satellites are operational. Sentinel-1 supports single polarization (HH, VV) and dual polarization (HH + HV, VV + VH). Its operational modes include StripMap (SM), interferometric wide (IW), extra wide (EW), and wave (WV), with the main acquisition mode over land being IW, which employs the terrain observation with progressive scanning SAR (TOPSAR) imaging technique [31]. Sentinel-1 images are freely available from the European Space Agency (ESA).

Compared to CSK and TSX (Table 1), although Sentinel-1 imagery has relatively lower resolution, its swath width can reach 250 km, more than five times the swath width of CSK and TSX. This means that the area covered by a single Sentinel-1 image would require 25 images of CSK or TSX images. If achieving large-area coverage by mosaicking CSK or TSX images [32], it may not only increase the workload (in terms of time and cost), but the mosaicking process may also introduce new errors. This increases the need for Sentinel-1 imagery in building SHM. Sentinel-1 offers a larger imaging coverage, shorter repeat cycle, and is free, making it more advantageous for large-scale, high-frequency monitoring.

Table 1. Parameters of commonly used SAR images.

Satellite	Band	Mode	Polarization	Resolution	Cycle	Swath Width	Pay
CSK	X	SM	HH	3×3 m	16 days	40 km	yes
TSX	X	SM	HH or VV	1.2×3.3 m	11 days	30×50 km	yes
Sentinel-1	C	IW	VV	5×20 m	6 or 12 days	250 km	free

2.2.2. Building Data

Based on the global building height map (3D-GloBFP) [33] in 2020 (Figure 1c), we adjusted some building heights in the GFMA combined with the building information published by the Council on Tall Buildings and Urban Habitat (CTBUH) [29], and also manually interpreted and corrected the building boundary polygon vectors compared with Google high-resolution images and the China Building Rooftop Area (CBRA) [34] dataset to ensure higher accuracy. Then, a building whose height is greater than the target threshold is selected as part of the super high-rise buildings which are the focus of this paper.

In this paper, the building boundary polygon vectors of 3D-GloBFP are corrected to merge multiple tower buildings sharing the same podium into one polygon from multiple polygons; that is, these tower buildings should be regarded as a single building structure, because the building structure monitoring should take an interconnected complete building as the minimum analysis unit.

The Chinese Uniform Standard for Design of Civil Buildings (GB 50352-2019) [35] stipulates that a building height greater than 100 m is a super high-rise building. Considering the root mean square error (RMSE) of 3D-GloBFP in China is greater than 10 m [33], the super high-rise building threshold was set to 90 m.

3. Method

The surface deformation for the entire GFMA was first obtained using PS-InSAR, and the PS points within the boundary of the target buildings were then filtered based on their vector outlines. The footprint of super high-rise buildings is often too small relative to the imaging spatial coverage of Sentinel-1, which may result in insufficient information and could affect measurement accuracy. For each super high-rise building, the deformation information recorded by PS points was used to monitor structural health by analyzing the deformation conditions of the buildings and assessing their safety. Finally, the factors affecting structural health were explored.

3.1. PS-InSAR

SAR imagery records the amplitude and phase of the backscattered electromagnetic waves of ground objects, and the phase represents the distance traveled by the radar wave, which can be used to calculate the distance between the ground object and the radar sensor. Differential interferometric synthetic aperture radar (DInSAR) obtains the relative ground motion through differential interferometric measurements using the phase information acquired from two or more SAR image acquisitions.

Persistent scatterer interferometric synthetic aperture radar (PS-InSAR) is an enhancement of DInSAR, designed to address the phase decorrelation issues that can arise during long-term monitoring [36,37]. It focuses on pixel points that exhibit strong and constant reflections over a long period in a series of SAR images and measuring the deformation at these points, known as persistent scatterers (PSs). PSs refer to stable highly backscattering points that can maintain high coherence over long time intervals, corresponding to buildings, exposed rocks, etc., in real scenarios. This makes PS-InSAR more suitable for urban areas, where it is used to measure deformation of man-made structures and other stable points.

Coherence indicates the phase similarity of the radar reflection between two pixels at the same location in two SAR acquisitions, which is calculated by complex cross-correlation over the neighboring interferometric pixels, ranging from 0 (decorrelation, where the interferometric phase is pure noise) to 1 (a stable phase signal) [38]. Decorrelation describes the situation where phase differences between images become large due to ground surface changes (e.g., vegetation growth), atmospheric disturbances, different acquisition incidence angle, and so on, making interferometric information usable.

Temporal and perpendicular baselines are the simplest methods for assessing image coherence. Image pairs that exceed the critical baseline threshold generally do not have high coherence, and the interferograms generated by such pairs are typically unreliable and classified as noise, which should not be used for further InSAR processing. A repeat-pass SAR satellite observes the same area at regular time intervals. The temporal baseline is the time difference between the acquisition of two images, while the (physical) baseline is the physical distance between sensor positions at the two acquisitions, as the sensor positions vary slightly each time. The perpendicular baseline, which is the component of the (physical) baseline perpendicular to the satellite's line-of-sight (LOS), is the most significant factor influencing image coherence [39].

A time series is constructed from multiple SAR images, and the image with the highest average coherence is selected as the master image and paired with the other images for interferometric processing (Figure 2a). Precise orbit ephemerides for Sentinel-1 from ESA were employed to correct orbital errors, along with co-registration using the 1 arc-second Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) from the U.S. Geological Survey (USGS) [40].

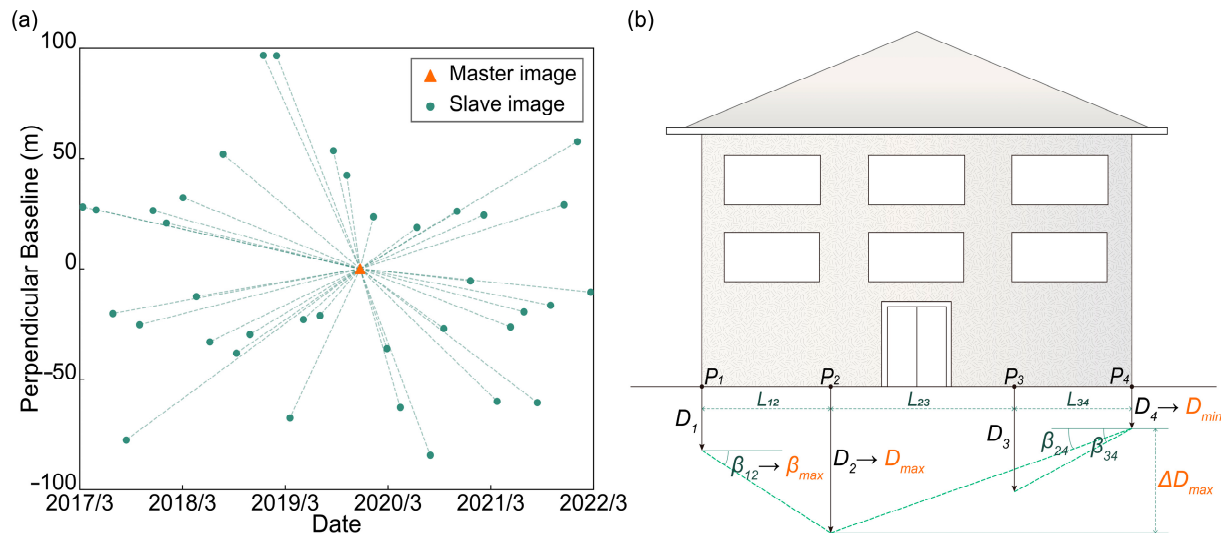


Figure 2. (a) Spatial and temporal baseline of Sentinel-1 images from March 2017 to March 2022; (b) diagram of the SHM parameters used in this study.

Points that simultaneously meet the criteria of the amplitude dispersion index (ADI) < 0.4 [36,41] and phase coherence > 0.75 [37] were selected as the PSs. Considering the scattering characteristics in urban scenes, the single-bounce scattering from building facades and roofs, as well as strong double-bounce scattering generated by the dihedral and trihedral structures formed by the building structure itself or building facade and the ground [42], resulting in stable and well-defined signal paths, maintaining a high backscatter amplitude with strong coherence over long-term monitoring, which is beneficial for PS-InSAR applications [43]. They are identified as PS points in PS-InSAR, thereby recording deformation data and providing observational information for SHM [44].

The interferogram results from the complex conjugate multiplication of two SAR images [45], which cancels the common backscatter phase in each pixel and leaves a phase term proportional to the differential path delay. The wrapped interferometric phase differences, presented in modulo, were unwrapped using the minimum cost flow (MCF) [46] method to retrieve the distinct phase, enabling the calculation of deformation velocities and displacements of PSs. In addition to the deformation phase we need, the interferometric phase difference also includes errors such as topographic phase, atmospheric error phase, and noise phase. The SRTM DEM data can be used to remove the topographic phase, while the Generic Atmospheric Correction Online Service (GACOS) atmospheric modeling data can help minimize the atmospheric interaction errors [47].

After obtaining the deformation (D_{LOS}) along the radar's LOS direction, the deformation velocity (V_{LOS}) over the observation period is estimated using least squares. In theory, these deformation data should be decomposed into components in the horizontal (east–west, north–south) and vertical directions. However, since the GFMA only includes ascending images, we lack enough parameters to derive the deformation in each direction [48,49], and the subsequent analysis of building SHM focuses on vertical settlement [9,24,26], so we assume that deformation occurs mainly in the vertical direction, ignoring horizontal deformations [19,50]. This assumption does not introduce significant errors but simplifies

the calculations [51]. Therefore, we transformed the LOS deformation and deformation velocity to the vertical direction (D_v , V_v) using the incidence angle (θ), as follows:

$$D_v = \frac{D_{LOS}}{\cos \theta} \quad (1)$$

$$V_v = \frac{V_{LOS}}{\cos \theta} \quad (2)$$

3.2. Structural Health Monitoring

The geometric deformation of buildings is a critical aspect of structural health monitoring, including building settlement, tilt, and so on. Both the structural changes in the buildings themselves and the variations in the surrounding ground are within the monitoring scope. During construction and use, building structures may be affected by various factors, leading to alterations of varying degrees. A certain amount of deformation is normal, but if the deformation exceeds the allowable thresholds, it will impact the normal use of the building. Using the spatio-temporal information provided by PS-InSAR, we constructed the following four parameters for structural health monitoring (Figure 2b): settlement value (D), differential settlement value (ΔD), recent settlement velocity (V), and angular distortion (β). These parameters are used to assess the safety of the buildings and to identify anomalies [24,26,44].

The squinted imaging mode of SAR may cause some PS points to shift outside the building polygons [44]. Additionally, the surrounding ground of the building refers to an area ranging from 1 to 3 times the depth of building excavation [52]; super high-rise buildings are all deep excavations. Therefore, a 10 m buffer zone was set for each building to contain more valid PS points considering the Sentinel-1 imagery resolution [44]. Generally, super high-rise buildings have large footprints and wide spacing between adjacent buildings. Given the accommodation of PS point shifts, a 10 m buffer zone will not significantly increase the area relative to the building's size, thus avoiding the introduction of irrelevant information. At the same time, it helps minimize the overlap of buffer zones between adjacent buildings, making it clearer to which building the PS points belong. Finally, the PS points located within this 10 m buffer range were all included in the geometric deformation calculation.

The negative deformation value is considered as settlement, and the settlement value (≥ 0) is the absolute value of the negative deformation accordingly. For each building, the cumulative settlement value (D) is defined as the maximum cumulative settlement (D_{max}) of all PS points on the building during the monitoring period.

The differential settlement value (ΔD) is the difference between the maximum cumulative settlement (D_{max}) and the minimum cumulative settlement (D_{min}), as follows:

$$\Delta D = D_{max} - D_{min} \quad (3)$$

The recent settlement velocity (V) is the maximum value of the settlement velocity (V_{max}) of the last six observation moments calculated by the least squares method.

The angular distortion (β) is defined as the maximum ratio of the absolute value of the settlement difference ($|\Delta D_{12}|$) to the horizontal distance (L_{12}) between any two points with similar heights. Note that in some studies, β is directly calculated as the ratio of the differential settlement (ΔD) to the horizontal distance between the maximum cumulative settlement (D_{max}) point and the minimum cumulative settlement (D_{min}) point [53]. However, this approach overlooks the possibility that other points, which may be closer horizontally, could yield a larger ratio, and it also does not account for differences in height [24]. Therefore, we modified this algorithm, as follows:

$$\beta = \max \left(\frac{|\Delta D_{12}|}{L_{12}} \right) \quad (4)$$

If there are no PS points on a building, such as due to decorrelation, or if there are no PS points that meet certain parameter requirements, then the building will have no monitoring results or lack certain parameter results. The values of each SHM parameter were categorized into four levels based on safety from highest to lowest: safety, relative safety, critical safety, and anomaly (Table 2). The threshold of each safety level is determined according to the relevant provisions of Chinese Code for deformation measurement of building and structure (JGJ 8-2016) [1], the Code for design of building foundation (GB 50007-2011) [54], and related studies [55–57]. The Code (JGJ 8-2016) [1] explicitly requires that the overall angular distortion of buildings over 100 m should not exceed 2‰ and the settlement velocity under stable conditions should not exceed 0.01–0.04 mm/day. The Code (GB 50007-2011) [54] stipulates that the settlement difference between the main building and the adjacent podium columns should not exceed 0.1% of their span. For recent settlement velocity, Li et al. [55] recommended a monitoring period of 3 years with a limit of 2.6 mm/month, while Fei et al. [56] suggested a threshold of 3 mm/month for monitoring periods of 3–5 years, and 2 mm/month for periods longer than 5 years. Zhang et al. [57] considered the allowable settlement for buildings with deep foundations to be between 42 mm and 71 mm. The threshold for cumulative settlement over 3 years is 48 mm [55,56]. Based on our PS-InSAR measurements and considering the building height and scale, we empirically set the thresholds shown in Table 2.

Table 2. Threshold for structural health monitoring parameters.

SHM Parameter	Safety Level			
	Safety	Relative Safety	Critical Safety	Anomaly
Settlement value, (mm)	<20	≥ 20	≥ 40	≥ 60
Differential settlement value, (mm)	<20	≥ 20	≥ 30	≥ 45
Recent settlement velocity, (mm/mon)	<1.0	≥ 1.0	≥ 1.8	≥ 2.4
Angular distortion, (‰)	<1.0	≥ 1.0	≥ 1.5	≥ 2.0

Note: All thresholds are positive values, as they represent settlement. Taking the opposite sign can convert them into deformation values.

The final assessment of building safety is based on the lowest safety level among the four parameters. If there are no monitoring results for all four parameters for a building, its safety level will be marked as not measured. An on-site investigation should be conducted immediately after identifying anomalous signals to determine whether they come from structural building elements (e.g., pillars, beams) or non-structural elements (e.g., infill walls, panels) [58]. Issues arising from non-structural elements are generally manageable, while structural problems can be quite challenging.

4. Results and Discussion

4.1. Safety Status of Super High-Rise Buildings

A number of 2551 super high-rise buildings in GFMA were selected, with a total area of 3.05 km², and 90% of the building height was less than 150 m (Figure 3b). The distribution of super high-rise buildings shows a clear pattern of clustering, with the central areas of Tianhe and Yuexiu District in Guangzhou radiating outwards (Figure 3a). In Foshan, these buildings tend to be concentrated on the side closer to Guangzhou, capitalizing on the location advantage of more convenient access to the more prosperous city.

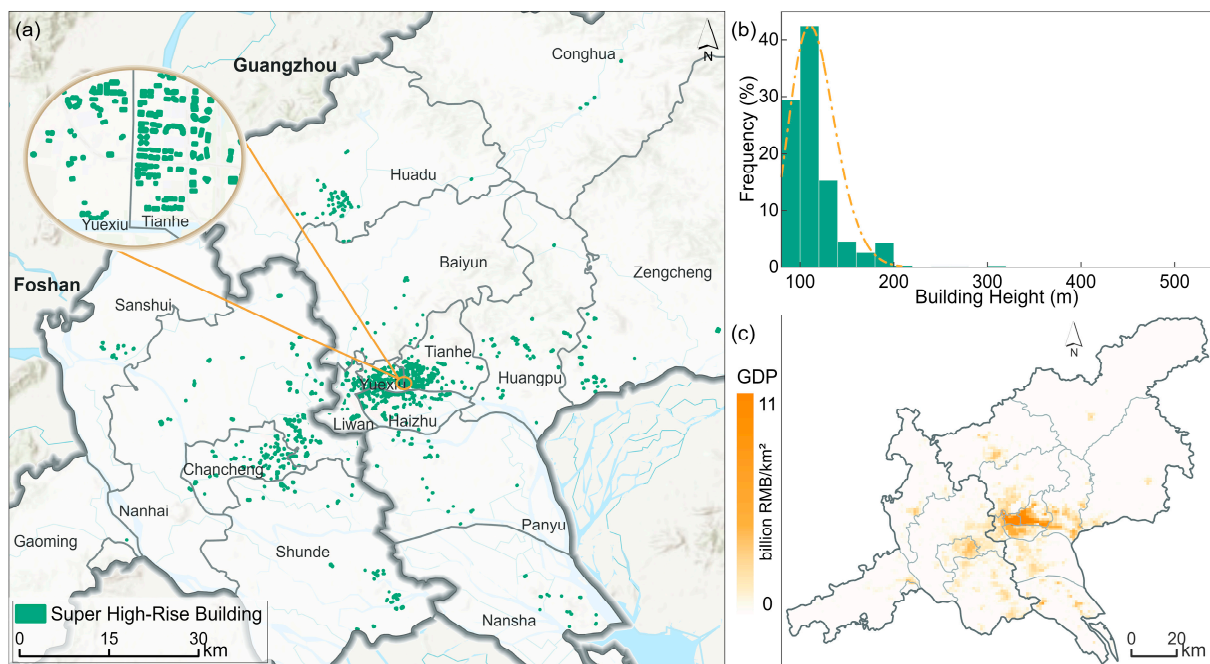


Figure 3. (a) Distribution and (b) height statistics of super high-rise buildings; (c) the GDP per km² in 2020. For a clearer display, the area in (a) is the minimum bounding rectangle of the location of super high-rise buildings, rather than the GFMA.

The distribution of super high-rise buildings can also reflect the economic space. The correlation analysis was conducted between the number of super high-rise buildings per km² and the GDP per km² [17] in 2020 (Figure 3c). The dense super high-rise building region and the high GDP region almost overlap, with a correlation coefficient of 0.71, indicating a relatively strong correlation. People continuously gather together in economic and commercial centers, thereby spawning a large demand for office and housing. Coupled with sufficient funds and favorable location advantages, many super high-rise office buildings and residential buildings have been built.

A deformation velocity map in the GFMA generated from the Sentinel-1 images between 2017 and 2022 is shown in Figure 4a. The overall deformation velocities range from −78.41 to 38.83 mm/yr, with an average velocity of −0.93 mm/yr. The average density of PS is 954/km², and points with deformation velocity within ±10 mm/yr accounted for 92.46% of all 10,716,334 PS points.

The GNSS time series data of GUAN station (113.34 E, 23.18 N) from the Crustal Movement Observation Network of China (CMONOC) [59], provided by The Second Monitoring and Application Center (The Western Data Branch of National Earthquake Data Center, Xi'an, China), were used as validation data to evaluate the estimation accuracy of PS-InSAR. PS-InSAR estimates the relative displacement of PS points with millimeter-level precision, but the absolute positioning precision of PS points using Sentinel-1 images is usually in the range of decimeters to meters [60,61]. Since the PS points and the GUAN station are not located in the exact same place, a 50 m buffer zone [32,50] was established around the GUAN station to minimize the effect of the geolocation errors between PS points and the GUAN station, so that the two datasets are comparable.

Root mean square error (RMSE) measures the residual distribution between predicted values and actual observations, often used as an accuracy evaluation metric for InSAR [26,27,50,62,63], with a smaller RMSE indicating a better model fit. RMSE is calculated as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (5)$$

where $\hat{y}_i$ is the i -th predicted value; y_i is the i -th observed value; and n is the number of observations.

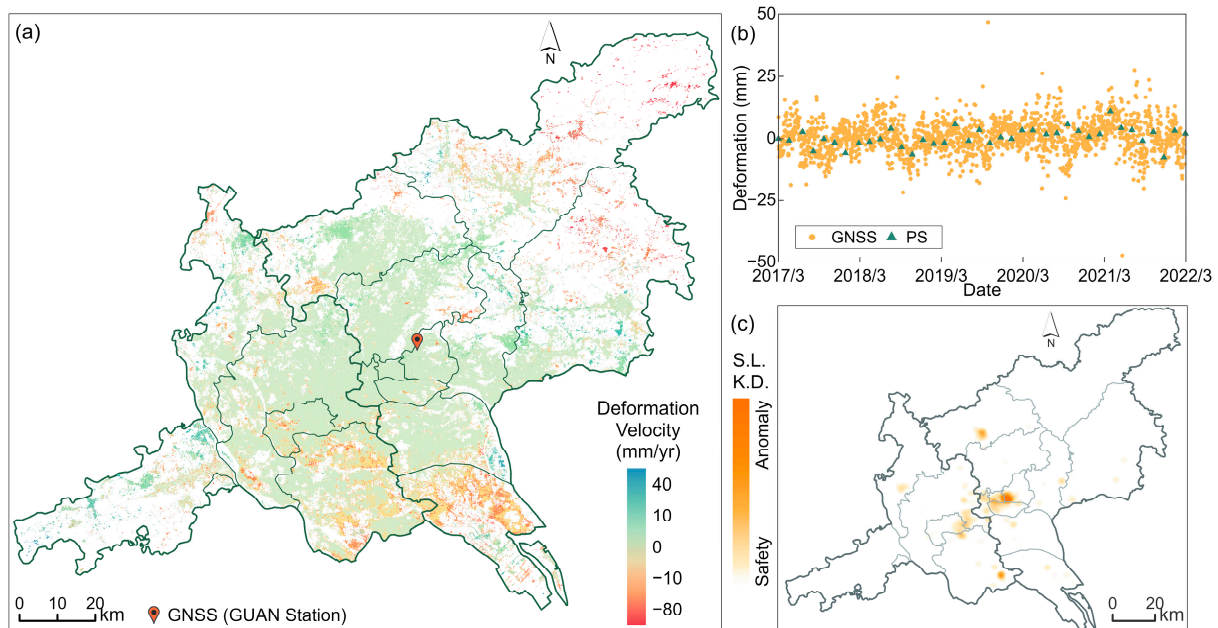


Figure 4. (a) Deformation velocity in the GFMA from 2017 to 2022; (b) comparison of the PS-InSAR and GNSS deformation time series; (c) the kernel density of safety level, S.L.K.D. is short for safety level kernel density for clearer display.

The GNSS vertical deformation time series is used as the actual observed values (y_i) to validate the PS-InSAR results (predicted values, $\hat{y}_i$). The GNSS station records observations once per day (orange circles in Figure 4b), which differs from the time interval of the Sentinel-1 images we used, so we extracted GNSS data based on the Sentinel-1 image intervals. There are 45 PS points within the buffer zone of the GUAN station. Comparing the deformation velocities of these 45 points with the GNSS deformation velocity (0.15 mm/yr), the minimum absolute difference is 0.03 mm/yr, the minimum difference is -0.38 mm/yr, and the maximum difference is 3.08 mm/yr, with an overall RMSE of 1.50 mm/yr. The cumulative deformation for each observation time of the 45 points is averaged to obtain an average cumulative deformation time series of PS points (green triangles in Figure 4b). This PS time series is compared with the GNSS time series for the cumulative deformation values at each time, giving a correlation coefficient of 0.69 and an RMSE of 4.51 mm. The deformation velocity of the PS average time series (0.94 mm/yr) differs from the GNSS deformation velocity by only 0.79 mm/yr. All of these show a consistent trend and reliable accuracy (Figure 4b).

A total of 23,754 PS points fell within the buffer zone of super high-rise buildings, providing monitoring data for 1910 buildings, of which 1020 buildings obtained all four parameters. The monitoring results show that the super high-rise buildings in the GFMA are generally safe, but there are still 105 buildings whose structural safety has reached the critical threshold and require continuous attention; additionally, 17 buildings were even classified as safety anomalies, which should be paid attention to immediately and required on-site investigation. Approximately 90% of the buildings in critical safety and anomaly are less than 150 m in height (Table 3); perhaps higher buildings face stricter supervision and quality control in the process of construction and use, so the safety condition of buildings above 150 m is relatively better. Buildings below 200 m are mainly classified as safety, while those above 200 m are more classified as relative safety. These taller buildings are typically designed with greater flexibility to withstand external forces such as typhoons. This reasonable degree of sway may make their SHM results appear less favorable compared

to buildings below 200 m, but they are all safe. Due to the lack of actual measured data on the structural deformation of the building, the precision of the four SHM parameters may not be evaluated. However, the accuracy of the PS points used for calculation has been validated, and the monitoring results have been further corroborated through on-site investigations.

Table 3. Building safety levels by height.

Building Height (m)	Safety Level					Total
	Not Measured	Safety	Relative Safety	Critical Safety	Anomaly	
≤100	160	368	212	37	4	781
100–150	402	770	296	55	13	1536
150–200	73	86	31	8	0	198
>200	6	9	12	5	0	36
Total	641	1234	554	105	17	2551

The kernel density analysis of the safety level of buildings (Figure 4c) shows that the places with not ideal structural safety conditions are mainly concentrated in the southwest of Tianhe district (i.e., Pearl River New Town) and the middle of Huadu district in Guangzhou, also in the southeast of Shunde district in Foshan. Pearl River New Town is a building-dense area, the central business district (CBD) of Guangzhou, with extensive metro lines and towering skyscrapers. High-intensity human activities have likely compromised the structural integrity of buildings. The soft soil layer in Shunde district is thick (>20 m) and prone to land subsidence [64], which may affect the stability of the building's foundation. In Huadu district, the geological conditions are even more complex, with buried karst potentially causing ground collapse.

4.2. Cause Analysis for Anomaly Buildings

The on-site investigation and comprehensive analysis of buildings with lower safety levels based on structural health monitoring results indicate that the main causes of building deformation may be regional settlement in soft soil areas, construction of surrounding (underground) infrastructure, and aging of buildings. Some typical buildings were selected for detailed elaboration.

4.2.1. Regional Settlement in Soft Soil Areas

In the southeastern part of Shunde district, Foshan, the structural safety of two super high-rise residential buildings (B1 and B2) was identified as anomalies (Figure 5a). The cumulative deformation time series of PS points on building B2 clearly divides into the following two clusters (Figure 5b): one remains relatively stable, while the other shows significant settlement. In this case, P1 point is used to calculate the cumulative settlement of the building, while P1 and P2 reflect the differential settlement. Both parameters have exceeded permissible limits, posing a threat to the stability of the buildings.

The stability of buildings is closely related to the geological conditions of their location, as regional settlement caused by soft soil layers is a significant factor in building deformation. Generally, after a building is constructed, the foundation continues to consolidate and settle under the building-induced loads until it reaches relative stability. The higher the compressibility of the foundation soil layer, the more correspondingly will the settlement of the building be [19,50]. The closer to the completion time of the building, the more the periodic settlement will be, as the foundation has not yet fully consolidated [65]. In the area shown in Figure 5a, almost all PS points have deformation velocities of less than -5 mm/yr, indicating the occurrence of regional settlement. Buildings B1 and B2 were constructed around 2015, making them relatively new buildings during the monitoring period. Although they may still be in the foundation consolidation phase, the post-construction settlement and differential settlement have far exceeded the reasonable limits for newly

constructed buildings. In addition to these two buildings, several nearby buildings are also experiencing settlement close to the allowable threshold, which is likely due to collective regional settlement caused by thick, soft soil layers.

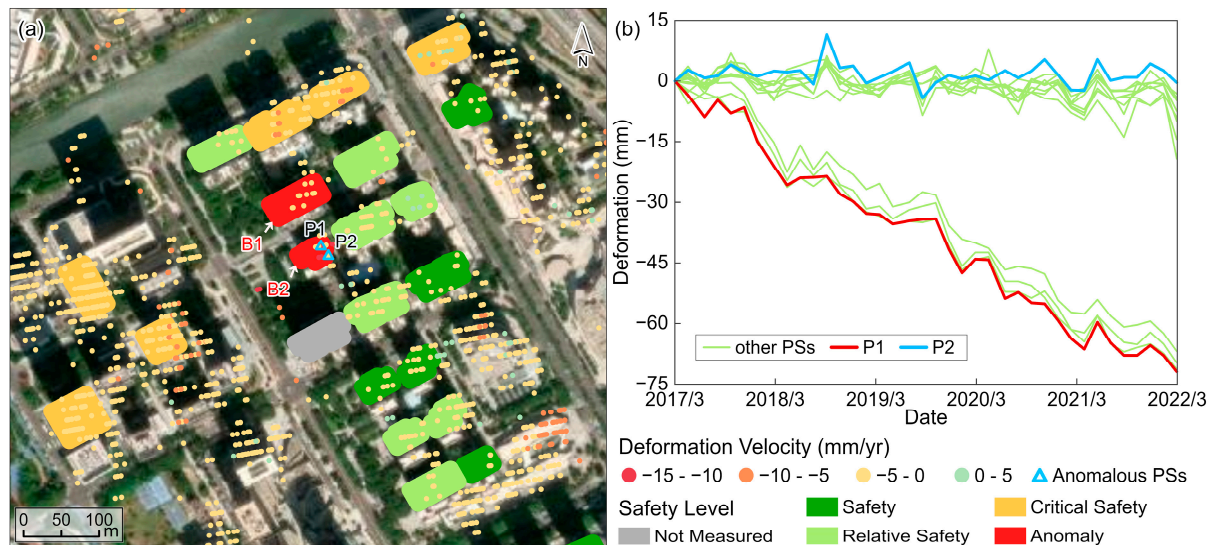
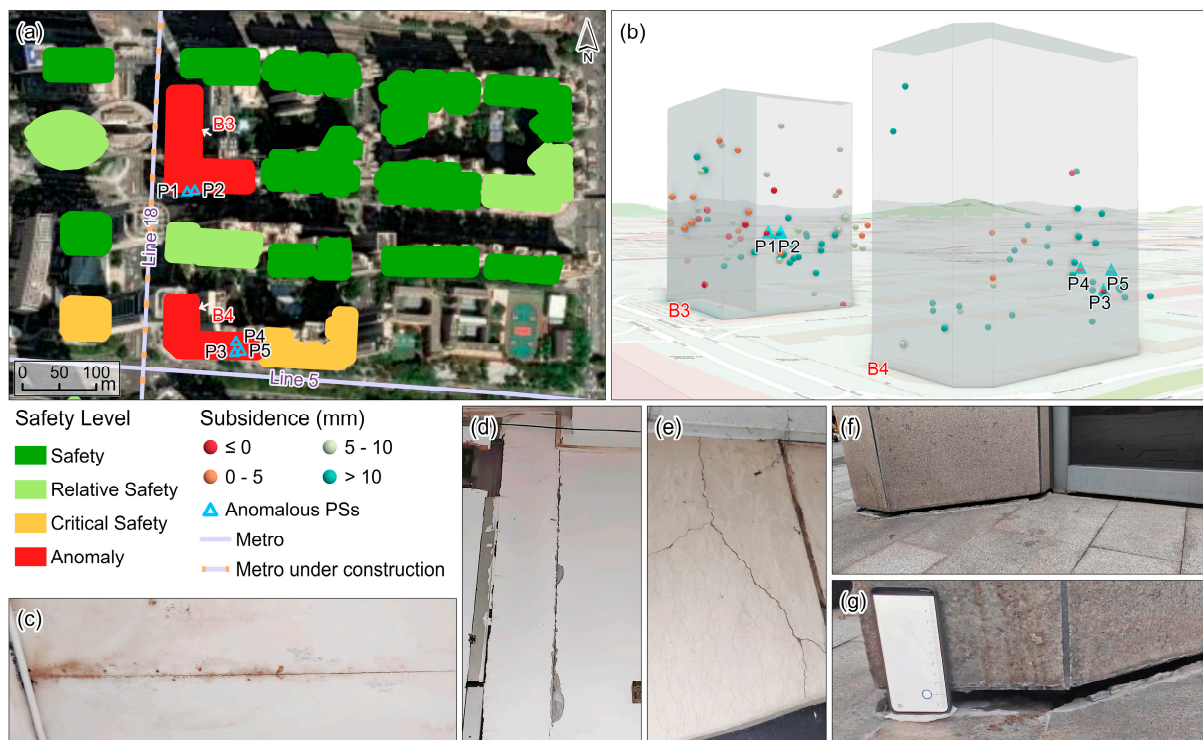


Figure 5. (a) Location and safety level of building B1 and B2; (b) cumulative deformation time series of PS points on building B2.

4.2.2. Construction of Surrounding (Underground) Infrastructure

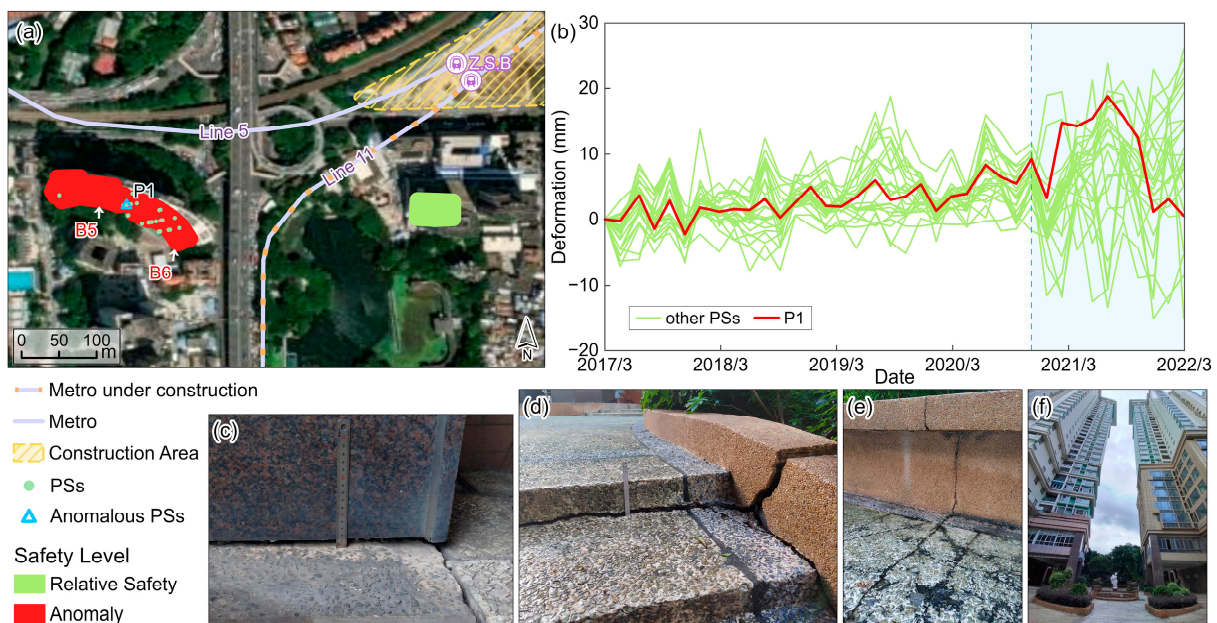
The structural condition of Guangzhou W Hotel (B3 in Figure 6) and Gaode Mansion (B4 in Figure 6) has been identified as anomalies. The two super high-rise buildings were completed in 2011 and 2008, respectively. During the monitoring period, the angular distortion of building B3 reached 3.1‰ (calculated by P1, P2 in Figure 6), while building B4 experienced a recent settlement velocity of -2.83 mm/month (calculated by P3 in Figure 6) and an angular distortion of 2.4‰ (calculated by P4, P5 in Figure 6), all exceeding limits.

Human activities, such as metro construction, may cause deformation in surrounding buildings. Metro tunnel excavation causes the loss of underground soil, which may lead to an imbalance of forces on building foundations, subsequently altering the stress on the upper structure. Additionally, construction vibrations can disturb nearby buildings. These factors may cause issues such as tilting, cracking, and other structural problems. There are two metro lines near buildings B3 and B4, including Guangzhou metro line 18, which began construction in 2017 and commenced operations at the end of 2021 (Figure 6a). The monitoring period in this study fully covers the entire construction process of line 18, with the construction route located right next to the already built B3 and B4. The angular distortion results of the two buildings show that the PS points closer to the metro are settling, while those farther away are uplifting. In B3, the cumulative settlement recorded by all PS points also indicates that the side of the building closer to metro line 18 is experiencing relatively more settlement (Figure 6b). On-site investigations found some noticeable cracks on the upper part of the inner wall of the podium in the Guangzhou W Hotel (Figure 6c–e), as well as a transverse gap over 20 mm wide at the outer wall corner of Gaode Mansion on the side closer to the metro (Figure 6f,g). It is highly likely that metro construction caused foundation settlement on the side of the buildings nearer to the construction area, resulting in both buildings tilting towards the metro.



4.2.3. Aging Buildings

Huiyangyuan was completed in 2001 and consists of two buildings over 31 stories (B5 and B6 in Figure 7a). Its recent settlement velocity has reached 2.52 mm/month (calculated by P1 in Figure 7), which does not meet the safety requirements for building structures.



Older buildings, constructed many years ago, may experience material degradation or structural deformation due to prolonged human use and environmental influences, posing safety risks. At the end of 2020, the PS points of building B6 suddenly began to fluctuate significantly, in contrast to the previous slow changes (Figure 7b). It is difficult to attribute this change to external conditions for the following reasons: (1) There have been no geological disasters in the surrounding area recently; (2) The closest large infrastructure project is Zhongshanba station of Guangzhou metro line 11 (also Zhongshanba transportation transfer hub, shown as Z.S.B in Figure 7a), which began excavating in November 2020. However, it is located nearly 300 m away, well beyond three times the foundation pit depth, limiting its impact; (3) The Dragon Boat Water rainfall in Guangzhou from May to June in 2020 reached a historic high. While precipitation has a lag effect on land subsidence [66], other PS points near Huiyangyuan did not show such changes. Therefore, the structural safety issues of Huiyangyuan are more likely caused by aging, which makes it extremely sensitive to changes in the external environment. However, excavation for Guangzhou metro line 11 began in September 2021 from Zhongshanba station to Ruyifang station, and part of the route is close to Huiyangyuan, which may disturb the building's foundation, so it is necessary to pay constant attention to the safety of surrounding buildings.

After 20 years of exposure to the elements, along with the excavations for metro line 5 and line 11, the stability of Huiyangyuan's buildings has been compromised, resulting in decreased safety. On-site investigations found multiple cracks on the community's ground, some exceeding 20 mm in width (Figure 7c–e). The inherent structural weakness of aging buildings, combined with disturbances from large infrastructure projects like the metro construction, has exacerbated the safety issues.

5. Conclusions

Conducting regular structural health monitoring of buildings, providing warnings for anomalies, and solving issues promptly reflect a responsibility for sustainable social development and the safety of people's lives and property. Using PS-InSAR technology and Sentinel-1 images, the building safety assessment method was constructed with a set of SHM parameters to evaluate the structural safety of each super high-rise building in GFMA. The accuracy of the results has been validated through GNSS measurements and on-site investigations. The reliable accuracy of open-source Sentinel-1 monitoring results enables the promotion of infrastructure SHM methods based on multi-temporal InSAR technology to break through the limitations of high-resolution commercial satellites, enabling faster calculations over large-scale areas for more efficient safety inspections.

Both Guangzhou and Foshan feature high-density buildings, with a noticeable clustering of super high-rise buildings that strongly correlate with urban economic spaces. In Guangzhou, the focus is on the Tianhe and Yuexiu districts, while in Foshan, the concentration is on the side closer to Guangzhou, fully leveraging location advantages. Overall, the super high-rise buildings in GFMA are considered safe, but some buildings in Pearl River New Town, central Huadu district, and southeastern Shunde district exhibit suboptimal structural safety conditions. The safety of 17 buildings has been identified as anomalies, requiring focused attention and proactive measures from relevant authorities. Factors such as settlement in soft soil areas, construction of surrounding (underground) infrastructure, and aging buildings can compromise structural safety. Regional settlement caused by geological conditions inevitably affects building deformation. Meanwhile, human activities like metro construction may disrupt the original stress on building structures, exacerbating deformation. In addition, aging buildings present certain safety risks and require regular maintenance.

In this paper, the three most typical building damage factors were selected for single impact analysis. However, society is a complex system, and in most cases, buildings are subjected to repeated influences from multiple factors. Therefore, quantifying the extent and importance of each factor's impact will be a key focus in future research. Additionally, while InSAR monitors the structural deformation of buildings from the outside and from

a distance, it can be combined with wireless sensors for internal monitoring, UAVs for close-range monitoring, and other technologies. This multi-technology, multi-directional monitoring approach not only validates the accuracy of InSAR measurements but also provides more comprehensive data, enabling more in-depth analysis and modeling.

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