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ARTICLE

Study on the Delimitation of Environmental Influence Zone for Engineering Construction in Karst Area

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ABSTRACT

With the increasing scale of underground space construction, urban karst geological disasters in China are becoming more and more serious, having a serious impact on people's daily lives and engineering construction. In this paper, a variety of monitoring methods are used to analyze the spatial and temporal variation characteristics of regional land subsidence during the construction of the Huanggekeng area in Longgang, Shenzhen, and the method of delimiting the environmental influence zone around the project construction is discussed. The results show that InSAR land subsidence monitoring has high measurement accuracy, and has the advantages of low cost and high efficiency in regional land subsidence monitoring. PS-InSAR technology can effectively delineate the environmental influence zone for engineering construction in the early stage of foundation pit excavation, and provide the basis for the delineation of the surrounding environment investigation range and the layout of the construction monitoring network in the key areas during the construction process. Through different stages of PS-InSAR monitoring data and construction progress, the boundary of the environmental influence zone can be dynamically updated, which is of great significance for the surrounding environment investigation, disaster prevention, and responsibility identification of the engineering.

Keywords: Karst Area; Leveling Surveying; PS-InSAR; Environmental Influence Zone

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1. Introduction

In recent years, the contradiction between urban land limitation and development has become increasingly intensified. In order to improve the urban carrying capacity, underground complexes, highways, subways, and other underground engineering construction has become the main way of urban development. Engineering construction in karst areas often induces disasters such as water inrush, mudslides, land subsidence, and sinkholes, which pose a serious threat to the safety of life and property of surrounding residents [1–4]. With the continuous expansion of urban renewal and underground space development, the problem of sinkhole disasters induced by engineering construction in karst areas has become increasingly prominent.

Compared with other types of geological disasters, the occurrence of sinkhole disasters is random, sudden, and hidden, which poses a serious threat to people's lives and property. The karst pipeline system can efficiently and rapidly transport groundwater, which greatly increases the influence zone of engineering construction in the karst area on the surrounding environment [5]. The delineation of the environmental influence zone of a construction project is of great significance to the reinforcement measures before construction, construction technology, surrounding environmental monitoring, and identification of disaster responsibility. In order to protect residents from property losses caused by quarry drainage, the zone of dewatering influence (ZOI) is defined as the areas approved by the Maryland Department of the Environment (MDE), based on Environment Article, § 15-813, Annotated Code of Maryland, around a surface mine in karst terrain. Dewatering of a surface mine, or pumping water out of a surface mine, may interfere with water supply wells and may cause sudden subsidence of land (sinkholes). The zones are based upon local topography, watersheds, geologic, and hydrologic factors. Limestone mining operations are required to repair sinkholes in the ZOI if MDE determines that the sinkhole resulted from quarry dewatering. Companies are required to replace a water supply that fails due to declining water levels caused by quarry operations at no cost to the property owner.

Relevant scholars mainly use monitoring data analysis, analytical methods, and numerical simulation to study the influence zone of settlement [6–12]. However, the influence zone based on the analytical method and numerical simulation is mostly tens to hundreds of meters, and the main area of the current construction monitoring focuses on a plane range of three times the depth of the foundation pit, which is far less than the actual environmental influence zone of the engineering construction. It is difficult to support the identification of disaster responsibility, resulting in continuous disputes between the construction parties and the affected residents. In recent years, Interferometric Synthetic Aperture Radar (InSAR) technology has become an important means of ground deformation monitoring due to its advantages of all-weather, large-scale, and low cost [13,14]. Compared with traditional monitoring methods, PS-InSAR technology does not require the installation of extensive monitoring equipment or the deployment of a large number of personnel. Moreover, it does not affect vehicle traffic on main roads during measurement. Instead, it only incurs data acquisition costs and requires a small team for data processing to obtain regional subsidence trends. By leveraging SBAS-InSAR technology and the CNN-BiGRU-Attention model, mining subsidence can be monitored and predicted autonomously with high precision [15]. However, its monitoring accuracy is affected by many factors, and the monitoring results lack the verification of measurement data [16–20]. Some scholars have combined InSAR and other monitoring methods to analyze land subsidence characteristics at the city level [21–24]. However, there are few studies focusing on small-scale subsidence in building-intensive areas caused by underground engineering construction. This study takes the Huanggekeng area of Longgang District, Shenzhen City, as an example, and uses Persistent Scatterer Interferometric Synthetic Radar (PS-InSAR) technology, leveling, and groundwater monitoring methods to analyze the characteristics of surface subsidence around the engineering construction and delineate the environmental influence zone in the karst area. It is of great significance for environmental investigation of engineering construction in karst areas, prevention, and remediation of karst geological disasters, and responsibility identification.

2. Research Area and Data Overview

2.1. Research Area

The karst distribution in Longgang District of Shenzhen is relatively wide, with an area of 64.39 km^2, mainly

concentrated in six streets. Due to the high-intensity construction of underground engineering and extreme weather conditions, karst geological disasters occur frequently in the area. These disasters have led to consequences such as personal injuries, damage to underground pipelines, vehicle collapses, and building tilting and cracking, which have adversely affected social harmony and economic development in the region.

The research area of this paper is located in the Huanggekeng area of Longgang District, which is an alluvial plain landform with small topographic relief. The surface cover is a loose deposit of the Quaternary late Pleistocene, which is mainly composed of gravel-containing silty clay, partially intercalated with a muddy soil layer, containing a large number of rotten wood, and the thickness is mostly 6–23 m. The underlying strata are Lower Carboniferous Datangian Ceshui Formation (C_1dc) shale and siltstone, Shidengzi Formation (C_1ds) limestone and marble. The site is controlled by the NE-trending fault structure, and the karst is strongly developed. The height of the karst cave exposed by the borehole is up to 22 m.

There are three construction projects in the research area, which are the station foundation pit of subway line 16, a otolaryngology hospital foundation pit, and the Huanggekeng southern urban renewal project (**Table 1**). Under the influence of foundation pit excavation, 10 sinkholes were formed within 500 m around the project, and 22 buildings cracked to varying degrees (**Figures 1** and **2**).

Table 1. Basic information of foundation pit of engineering construction.

Name	Length/m	Width/m	Depth/m	Construction Progress
Station foundation pit of subway line 16	514.36	16.5–77.6	12.7–18.4, 22.4 (two underground floors)	Excavation started in February 2020. In October 2020, the excavation of the north and south parts of the foundation pit was completed, and the middle part reached 8m. Excavated to 22.4 m in March 2021.
Otolaryngology hospital foundation pit	180	130	21 (four underground floors)	Excavation started in February 2020. Excavated to 7 m in July 2020. Excavated to 21 m in April 2021. Water sealing work on the bottom of the foundation pit completed in November 2021.
Huanggekeng southern urban renewal project	380	350	5–15 (one–three underground floors)	Excavation started in July 2020. Excavated to 5 m in October 2020. Water sealing work on the bottom of the foundation pit completed in April 2022.

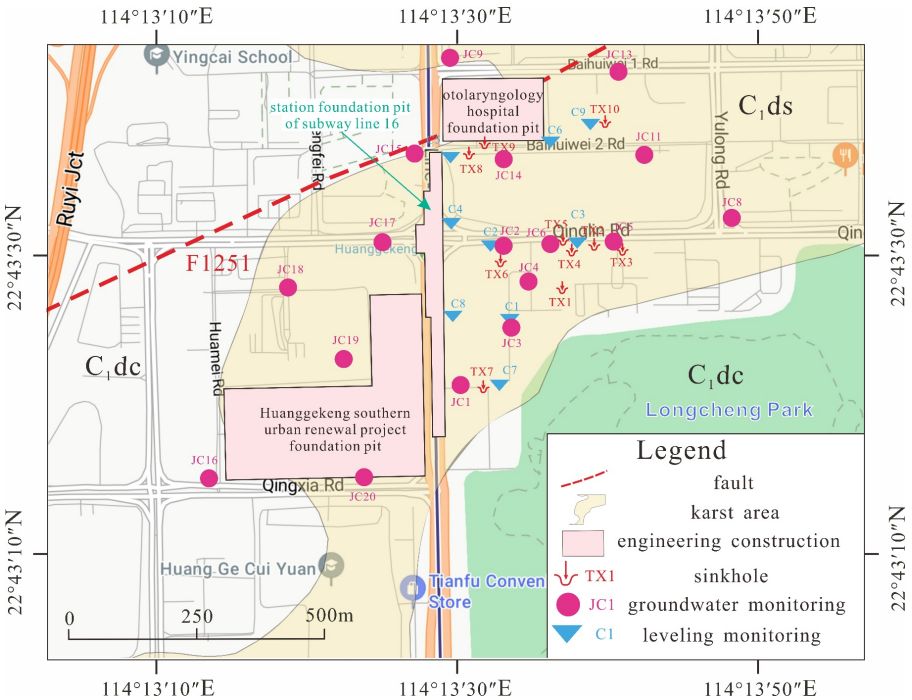


Figure 1. Geographical distribution of the studied sites in Longgang District, Shenzhen City, Guangdong Province, China.

Source: The base map is derived from Bing Maps (https://cn.bing.com/maps).



Figure 2. Sinkhole induced by engineering construction. This sinkhole is located at TX3, marked in **Figure 1**.

2.2. Monitoring Data Source

Since May 2020, multiple karst geological disasters have occurred in the surrounding areas of the construction project. In order to analyze the influence zone and change trend of the surrounding environment of the construction project, the research team has arranged leveling and groundwater monitoring networks (**Figure 1**). In order to trace the spatiotemporal changes of land subsidence in the early stage of engineering construction, this paper obtained 37 COSMO-SkyMed orbit-lowering SAR images from November 2019 to December 2021. The basic parameters of InSAR data are shown in **Table 2**.

Table 2. Basic Parameters of InSAR Data.

Parameter	Value
Satellite type	COSMO-SkyMed
Imaging mode	Strip mode
Data band	X band (3.1 cm)
Spatial resolution	3 m
Orbit raising/descent mode	Descent mode
Polarization mode	HH polarization
Number of images	37
Monitoring date	November 26, 2019–December 1, 2021
Data processing method	PS-InSAR

3. Data analysis

3.1. Analysis of Land Subsidence Monitoring Data

Before analysis, establish InSAR monitoring point data screening rules to obtain the real surface deformation. This work is an important prerequisite for accurately delineating the environmental influence zone for engineering construction.

In China, when the number of above-ground floors of the building exceeds three, the building generally adopts a pile foundation, especially when the end-bearing pile is used, the InSAR monitoring points in this area cannot reflect the real surface deformation. **Figure 3** shows the InSAR monitoring curve of a pile foundation building; the monitoring results indicate that the high-rise building itself undergoes periodic changes due to factors such as temperature and atmosphere. These points display periodic fluctuations in their data, potentially leading to inaccuracies in defining the environmental influence zone. The key to using PS-InSAR data processing in this method lies in eliminating the interference from these points and obtaining PS-InSAR points that accurately reflect true ground subsidence.

The floor height of Chinese buildings is generally between 2.8 m and 3.2 m. Therefore, the InSAR monitoring points with elevations less than the ground elevation value of the point plus 10 are selected as the data source for surface deformation analysis.

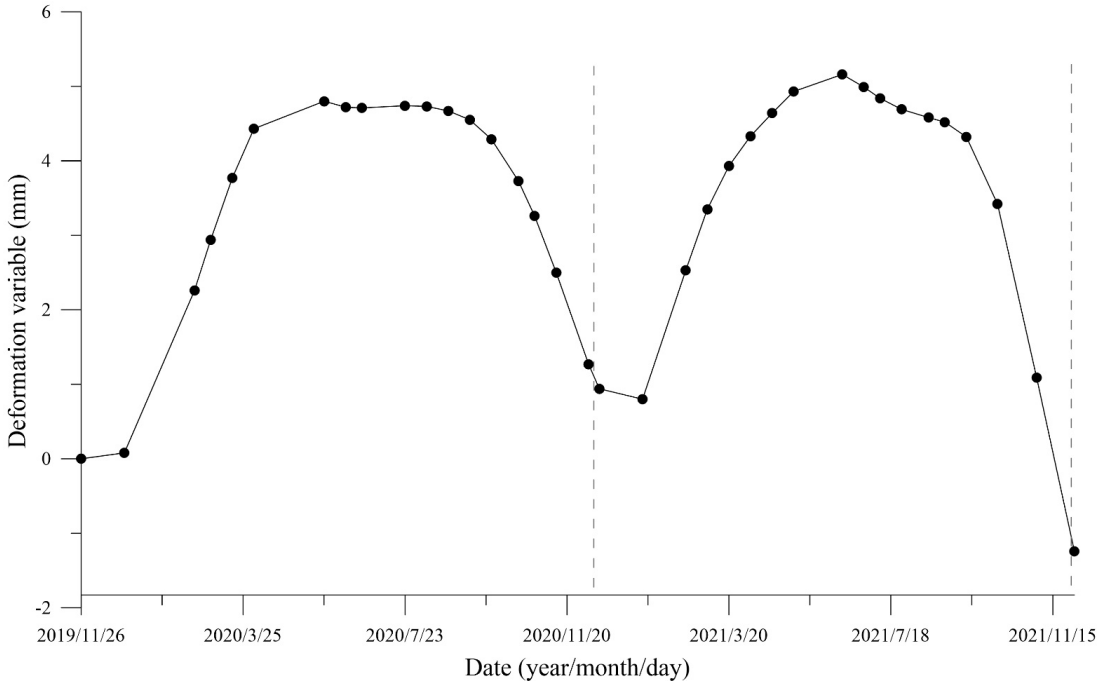


Figure 3. InSAR monitoring result of pile foundation building.

In this paper, the land subsidence monitoring level point C7 and the adjacent PS-InSAR monitoring points are selected for deformation analysis. The comparison results of subsidence monitoring are shown in **Figure 4**. The subsidence trend of leveling and PS-InSAR monitoring from August 2020 to December 2021 is basically the same. The relative difference of cumulative deformation measured by the two methods is 1.74 mm. The comparison results show that PS-InSAR land subsidence monitoring has high measurement accuracy. Due to the coordinates of the two methods being approximately 0.5 m, the above measurement error in the uneven settlement area is acceptable.

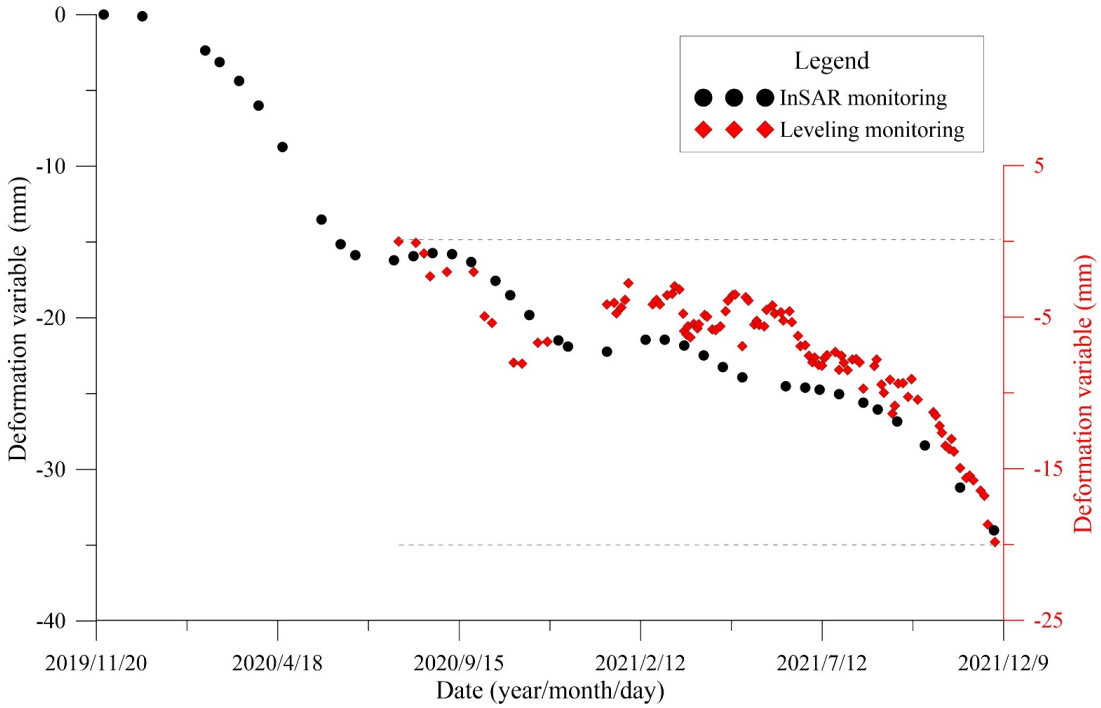


Figure 4. Comparison curve of InSAR and leveling deformation monitoring results.

In October 2020, the excavation of the north and south parts of the subway station foundation pit was completed, and the InSAR ground surface deformation monitoring values tended to converge. However, sinkhole disasters still occur in the surrounding area. The construction unit started grouting curtain construction in December, and the regional groundwater level began to rise, and the surface was slightly uplifted due to grouting curtain construction. With the continuous excavation of the middle part of the foundation pit of the subway station, the water sealing effect of the grouting curtain is destroyed, and the ground surface continues to sink (**Figure 5**).

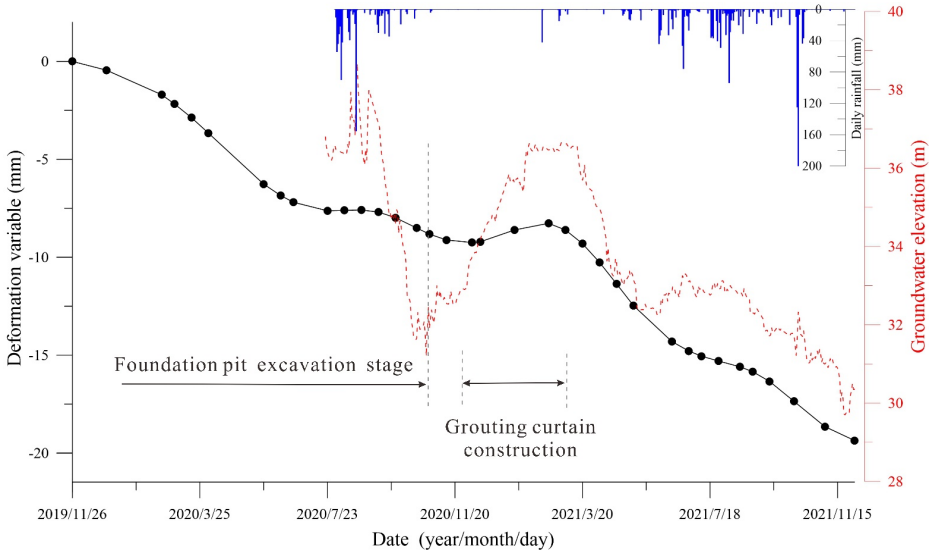


Figure 5. InSAR and groundwater monitoring results.

3.2. Groundwater Monitoring Analysis

In this paper, the groundwater monitoring points JC3 and JC4 are selected to analyze the dynamic changes of groundwater level around the project. As shown in **Figure 6**, the monitoring results can reflect the excavation of the foundation pit, water stop measures, and the change of the regional groundwater level after completion. Combined with rainfall monitoring, the monitoring of engineering drainage can be realized, which can provide a decision-making basis for engineering disposal and disaster prevention.

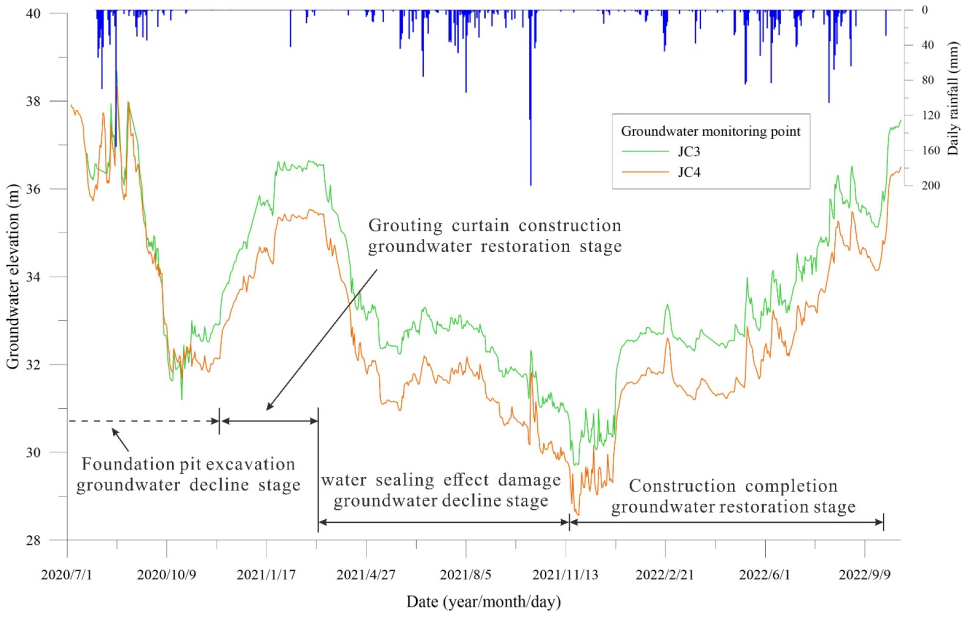


Figure 6. Groundwater dynamic change curve.

3.3. Comparative Analysis of Land Subsidence and Groundwater Monitoring Data

In this paper, the regional deformation rate map is obtained by using PS-InSAR data, and the groundwater monitoring data from October 24, 2020, is selected to draw the range of the groundwater depression funnel. As shown in **Figure 7**, affected by the water-resisting fault, two groundwater depression funnels are formed in this area. The long axis direction of the funnel is northeast, which is consistent with the trend of the fault structure. The deformation rate of the mainland subsidence area around the construction project is greater than 6 mm/a, up to 35 mm/a, which is significantly different from the overall deformation rate of the area, and the subsidence range monitored by PS-InSAR is basically consistent with the distribution characteristics of the groundwater depression funnel.

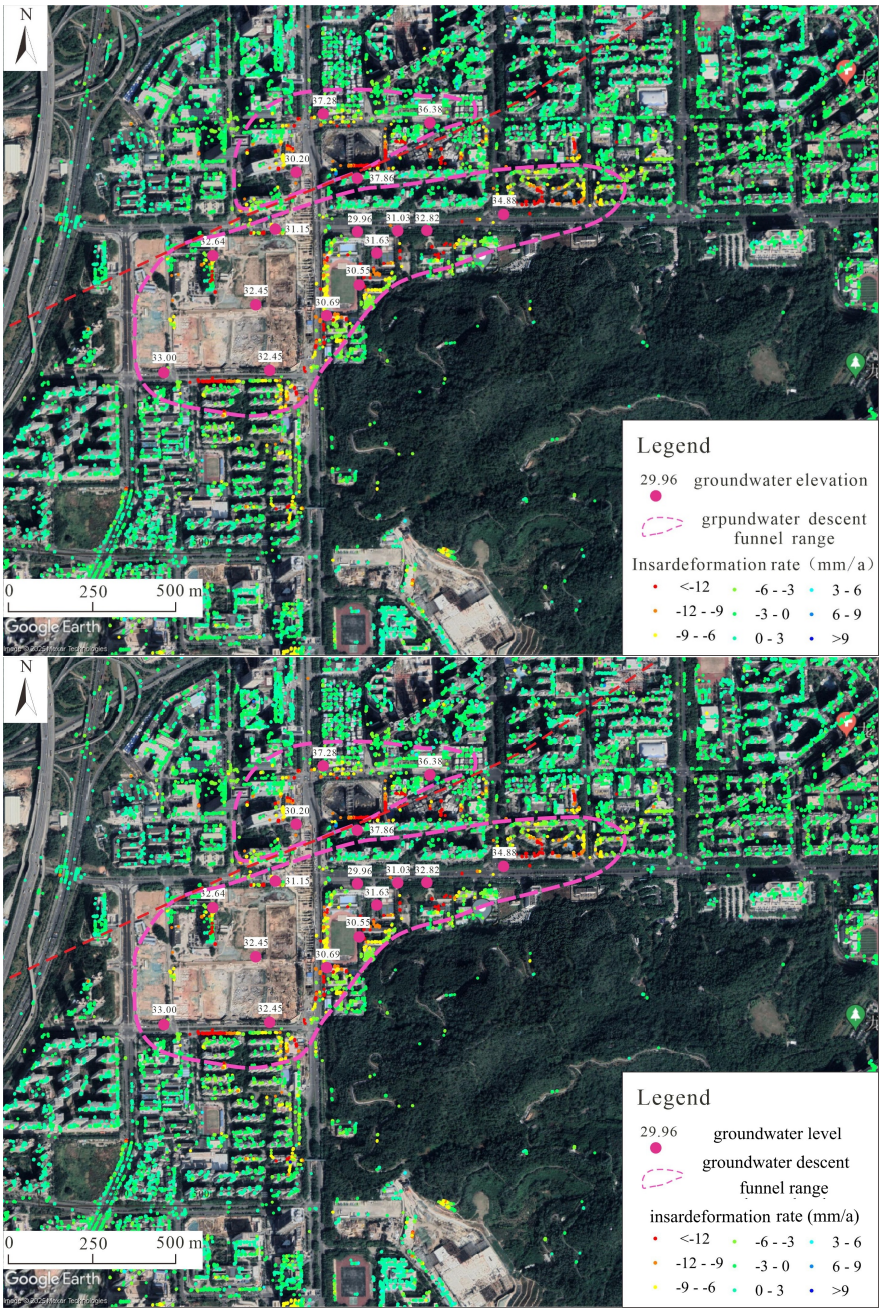
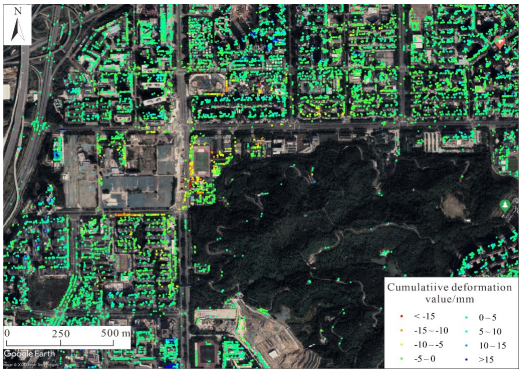


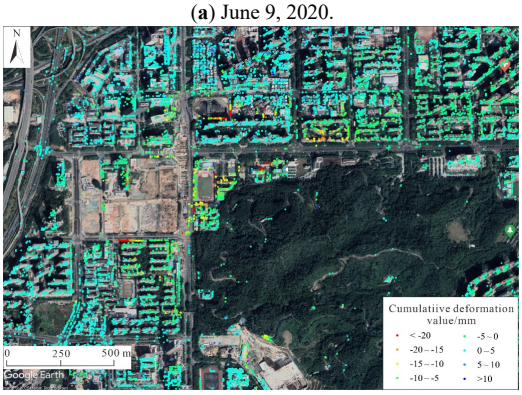
Figure 7. Land subsidence rate and groundwater depression cone distribution map. The base map is derived from optical satellite imagery of Google Earth.

3.4. Delimitation of Environmental Influence Zone for Engineering Construction

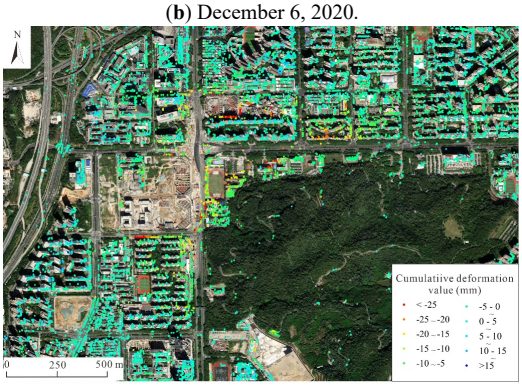
Based on the engineering construction timeline, the PS-InSAR monitoring data in the research area were analyzed, and the cumulative subsidence deformation was calculated every six months to obtain the spatiotemporal variation characteristics of land subsidence, as shown in **Figure 8**. In February 2020, the construction of the foundation pit for the subway station and the otolaryngology hospital began; In June 2020, there was a significant settlement range in the research area, with a maximum cumulative deformation value of 23 mm; In December 2020, as the excavation depth of the station and otolaryngology hospital foundation pit increased, the settlement area gradually expanded, and the maximum cumulative deformation value could reach 36 mm; In June 2021, the increase in excavation depth of the foundation pit of the otolaryngology hospital resulted in the settlement range of the area mainly extending to the east, with a maximum cumulative deformation value of 55 mm; In December 2021, the foundation pit of the Huanggekeng southern urban renewal project continued to be excavated downwards, resulting in the settlement range mainly expanding towards the south side, with a maximum cumulative deformation value of 68 mm.



(**a**) June 9, 2020.

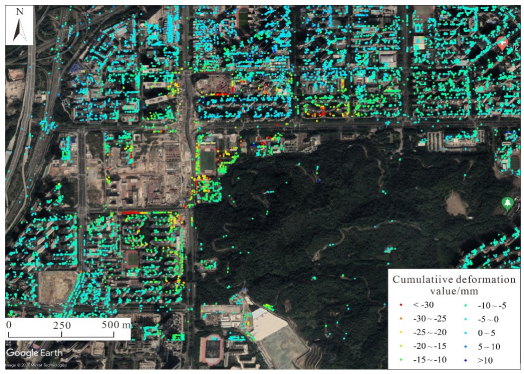


(**b**) December 6, 2020.



(**c**) June 12, 2021.

Figure 8. *Cont.*



(**d**) December 1, 2021.

Figure 8. The spatiotemporal variation characteristics of land subsidence monitored by PS-InSAR.

Source: The base map of (a), (b), and (d) in Figure 8 is derived from optical satellite imagery of Google Earth. The base map of (c) in Figure 8 is obtained by our team's drone aerial photography. These figures were created using the QGIS version 3.14.0-Pi software (https://qgis.org/en/site/).

According to the Shenzhen local standard *Technical Standard for Monitoring and Surveying of Urban Rail Transit Engineering* (SJG 135-2023), the allowable settlement for buildings surrounding a project is controlled within 10–30 mm[25]. However, our team's analysis of numerous building cracking cases reveals that structures with poor foundation conditions can develop fine cracks once settlement reaches the lower limit of 10 mm. Since the objective of this study is to enhance early prevention of environmental disturbances during construction, the cumulative deformation value of 10 mm is selected as the boundary of the environmental influence zone for analysis (**Figure 9**). The results show that PS-InSAR technology can effectively delineate the environmental influence zone for the project construction in the early stage of foundation pit excavation. Although the area of the environmental influence zone in different construction stages is different, its plane shape is basically the same, and the boundary of the environmental influence zone can be corrected by combining the PS-InSAR monitoring data from different periods and construction progress.

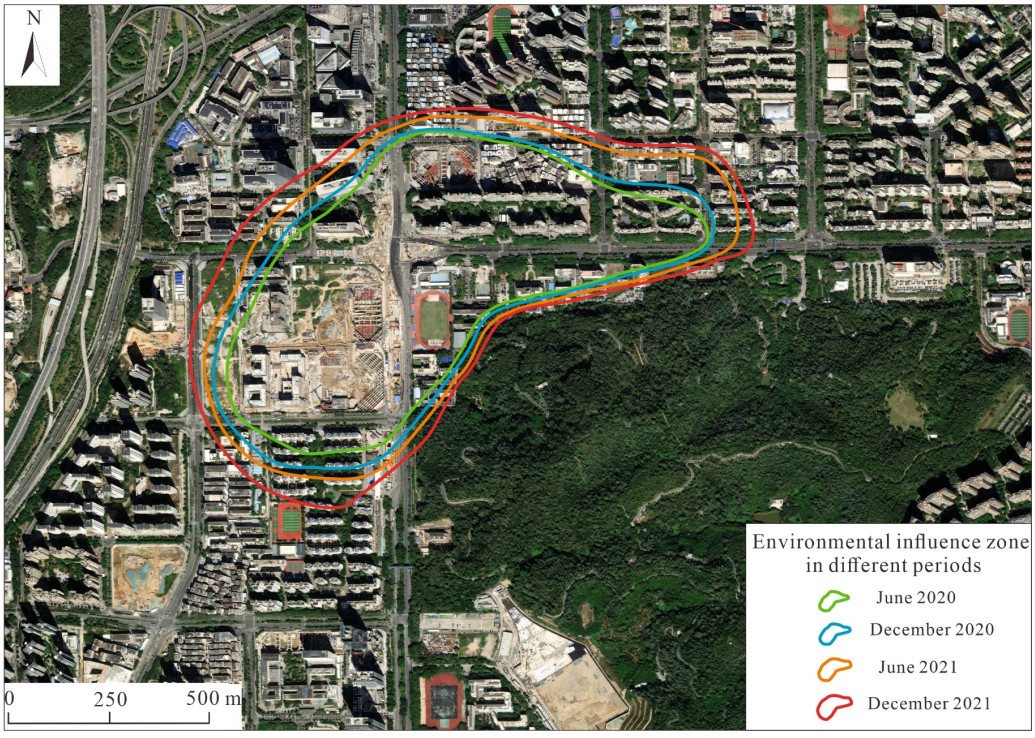


Figure 9. Superposition analysis of the land subsidence range in different periods.

Note: The base map is obtained by our team's drone aerial photography.

After excluding monitoring points affected by the thermal expansion and contraction of elevated structures, those PS-InSAR points showing a cumulative settlement of 10 mm or more are connected to demarcate the initial boundary of the subsidence influence zone. If groundwater or land subsidence data are available within this zone, the boundary contour can be further refined, allowing for dynamic updating of the influence zone.

4. Discussion

A sinkhole is characterized by its suddenness, concealment, repetitiveness, and unpredictability. The prevention and remediation of sinkhole remain a world-class technical challenge in the field of earth sciences. The main contribution of this paper is to propose a method for delineating the environmental influence zone of underground engineering construction in urban karst areas. Compared with analytical methods and numerical simulation, this method can clearly depict the outline of the influence zone of underground engineering construction, and provide a basis for delineating the key prevention and remediation areas of sinkhole disasters induced by urban underground engineering construction and the layout of monitoring networks.

The application of this method is to assume that the karst grouting treatment has not been carried out in the history of the analysis area, and it is only suitable for open excavation or underground excavation. This method is not suitable for shield tunnel construction because the assembly of tunnel segments is completed quickly after shield tunneling, and the influence on the surrounding environment is negligible without water gushing and good quality of secondary grouting (the settlement value is often controlled within 5 mm). In addition to karst areas, this method is also applicable to areas with weak soil layers such as silty soil.

This method is based on the comprehensive analysis results of PS-InSAR, leveling, and groundwater monitoring. In the urban built-up area, the layout of leveling and groundwater monitoring points is limited by the working environment, and the leveling is often measured manually. The measurement efficiency restricts the layout density of leveling points. Groundwater monitoring can reflect the disturbance of regional groundwater during the construction process, but the cost of drilling and monitoring equipment is high. With the support of limited monitoring costs of the project, only a small number of groundwater monitoring points can be set up. PS-InSAR points on high-rise buildings with rock-socketed piles are susceptible to thermal expansion and contraction of building structures and other factors. In data processing, it is necessary to eliminate such interference points in combination with ground elevation data to obtain PS-InSAR points that can truly reflect surface subsidence. The data accuracy of PS-InSAR points can be checked and corrected by leveling data. Under the condition that there are no PS-InSAR points in the vegetation coverage area, the change of groundwater monitoring data can assist in the delineation of the influence zone.

The cumulative settlement control value of surface and surrounding buildings in China's current engineering monitoring technical specifications is 30 mm. When the absolute value of deformation monitoring reaches 80% of the control value, early warning of monitoring will be carried out. Our research team systematically analyzed more than ten cases of karst geological disasters induced by underground engineering construction in the Longgang District of Shenzhen in recent years. When the cumulative settlement value of some buildings exceeded 10 mm, cracks began to appear. This method is intended to be used for the delineation of the environmental influence zone for engineering construction in the early stage of foundation pit excavation. Considering the further increase of settlement value during construction and the settlement after completion of the project, this paper selects the cumulative settlement value of 10 mm as the basis for the analysis of the influence zone, so as to achieve the purpose of prevention and remediation of karst geological disasters in the early stage of underground engineering construction. When using this method in other areas, the criteria for delimitation of the influence area boundary can be adjusted by referring to the cracking cases of local buildings.

5. Conclusions

In this paper, PS-InSAR, leveling, and groundwater monitoring methods are used to analyze the temporal and spatial variation characteristics of regional land subsidence during the construction of the Huanggekeng area in Longgang, Shenzhen, and the method of delineating the environmental influence zone for engineering construction in the

karst area is discussed. This method can identify the influence zone of underground engineering construction on the surrounding environment in the early stage, and provide the basis for the delineation of the key prevention areas of karst geological disasters around the project and the layout of the monitoring network during the construction process. The research results are of great significance to the investigation, prevention, and remediation of karst geological disasters induced by urban underground engineering construction in karst areas.

(1) PS-InSAR technology can effectively delineate the environmental influence zone for engineering construction in the early stage of foundation pit excavation, and provide the basis for the delineation of the surrounding environment investigation range and the layout of the construction monitoring network in the key areas during the construction process. Through different stages of PS-InSAR monitoring data and construction progress, the boundary of the environmental influence zone can be dynamically updated.
(2) Groundwater monitoring can directly reflect the change in the law of groundwater level around the construction project during the construction process. The distribution map of groundwater depression funnels can provide a basis and verification for delineating environmental influence zones in areas with vegetation cover lacking PS InSAR points.
(3) The method of delineating the environmental influence zone for engineering construction proposed in this paper is suitable for the construction project with the excavation depth of the foundation pit greater than the bedrock surface and shallow groundwater depth in karst areas, and areas with weak soil layers such as silty soil. The final boundary of the influence zone needs to be corrected according to the detailed geological investigation and construction monitoring data.

This approach not only enhances the understanding of environmental influence due to construction in karst regions but also supports the development of more effective risk management strategies, thereby contributing to safer and more sustainable urban development in geologically sensitive areas.

Author Contributions

Z.T.: Conceptualization, Formal analysis, Investigation, Writing—original draft preparation. Z.-W.L.: Writing—review and editing. Both authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The COSMO-SkyMed orbit lowering SAR images are purchased by the Shenzhen Technology Institute of Urban Public Safety. The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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