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Intelligent Early Warning and Decision Platform for Long-Term Ground Subsidence in High-Density Areas for Sustainable Urban Development

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Abstract: Long-term ground subsidence (LTGS) is a relatively slow process. However, the accumulation of long-term subsidence has an adverse impact on the normal operation and safety of a subway, hindering sustainable urban development. A wide gap exists between early warning theory and its application in the control of LTGS during subway operation due to time span limitation. Providing decision support for LTGS in high-density urban areas during subway operation is difficult, and a collaborative decision system for real-time early warning and intelligent control is currently lacking. This study establishes the functional components of an intelligent early warning and decision platform, proposes a software system module, constructs an overall software framework structure, and develops a mobile intelligent early warning and decision platform. Moreover, this study introduces an early warning method for LTGS in high-density urban areas during subway operation. This method integrates an intelligent early warning decision-making platform, namely Differential Synthetic Aperture Radar Interferometry (DInSAR), land subsidence monitoring, operation tunnel subsidence monitoring, and other multisource data coupling. The method is applied to sections of the Hangzhou Metro Line 4 Phase I Project (Chengxing Road Station (CRS)–Civic Center Station (CCS)–Jiangjin Road Station (JRS) and Xinfeng Station (XS)–East Railway Station (ERS)–Pengbu Station (PS)). This work can serve as a reference for ensuring urban safety and promoting sustainable development.

Keywords: LTGS; intelligent warning; high-density urban areas; decision platform; sustainable urban development

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1. Introduction

With the rapid development of the economy, the mileage of operating subways is increasing in China. The LTGS of operating metro tunnels will inevitably be induced by various factors, like the vibration load, adjacent buildings and structures, engineering disturbances, etc., especially in the high-density urban areas. According to Zhang et al. [1,2], the long-term subsidence of operating subways is a relatively slow process, but the long-term cumulative deformation can also cause various tunnel diseases in operating metro tunnels, such as tunnel leakage, damage, cracking, segment dislocation, etc. All of these tunnel diseases can deteriorate the performance of the subway system, and affect ride comfort and safety [3]. Therefore, there is an increasing focus among engineers and researchers on monitoring and early warning technologies for operating subway tunnels.

However, it is difficult to monitor the LTGS of operating metro tunnels due to the linearly distributed characteristics. Traditional monitoring methods, like GPS and precise leveling observation, cannot determine the accurate range of regional subsidence, and

implement all-weather field monitoring, which makes it difficult to manage and control the regional ground subsidence in high-density urban areas [4,5]. At present, research on LTGS mainly focuses on subsidence prediction, body subsidence, and dynamic response. Based on the dynamic triaxial tests of argillaceous siltstone, Shi et al. [6] proposed a prediction model for cumulative plastic strain. Di et al. [7] presented the maximum subsidence with 5.75 years of completion by analyzing the subsidence data of Nanjing Metro Line 10. Then, Di et al. [8] compared the subsidence differences of five subways in the Yangtze River Delta region on soft deposits. Additionally, the numerical simulation method was also used by some researchers to investigate the LTGS [9,10]. All of the methods and results above have their own shortcomings and cannot effectively complete the monitoring task of long-term subsidence during subway operations. In order to achieve a high efficiency and all-weather monitoring of long-term subsidence, the interferometric synthetic aperture radar (InSAR) technology was introduced to monitor and analyze land subsidence in different cities, such as Xi'an, Fuzhou [11,12]. Due to the lack of natural surface features, GPS technology was used by Song et al. [5] to produce InSAR-GPS-GIS technology to monitor LTGS in high-density urban areas during subway operation, and achieved good results. In addition, Jiang et al. [13] introduced a new Power Exponential Knothe Model that fits and fuses overlaps in the deformation's curves and, at the same time, uses LSTM neural network predictions and fuses temporal gaps. Chatterjee et al. [14] proposed a framework for investigating reconnaissance for the characterization of subsidence in the slow-subsidence city of Mehsana, Gujarat, India, with DInSAR. Zuccarini et al. [15] integrated ground-based and remotely sensed monitoring data, and investigated the long-term temporal evolution and spatial distribution of the subsidence process. Based on the aforementioned references, most of the research mainly focuses on long-term subsidence monitoring technology during subway operation. In order to obtain the all-weather safety status of operating metro tunnels and management decisions, it is meaningful to combine the long-term subsidence monitoring technology and early warning system, especially in high-density urban areas.

In this work, an intelligent early warning and decision platform for LTGS during subway operation is presented, which includes software operation and configuration, system functions and modules, and overall framework. Based on the proposed platform, sections (CRS–CCS–JRS and XS–ERS–PS) of Hangzhou Metro Line 4 Phase I are used as examples to apply the intelligent early warning and decision platform for LTGS during subway operation in high-density urban areas, which has important practical significance for the safety of urban subway operation.

2. Methods

The development of the intelligent early warning and decision platform mostly occurred on a computer loaded with the Windows 7 operating system. The released Android Package (APK) file version is generated through Android Studio and runs on the Android platform. The system version is higher than Android 4.4.

2.1. Software System Functions and Modules

2.1.1. Software System Functions

The functions of the intelligent early warning and decision platform system primarily include the early warning indicator input of LTGS, early warning indicator update of LTGS, early warning indicator weight setting of LTGS, and police judgment plan, as shown in Figure 1.

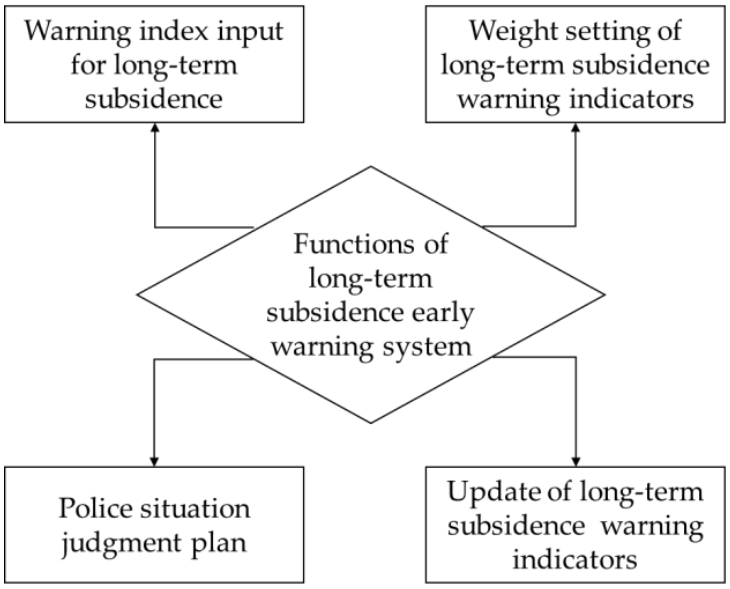

Figure 1. System functions.

2.1.2. Software System Modules

The entire system of the intelligent early warning and decision platform consists of the database, data storage service, data interface, alarm–judgment–plan, early warning indicator weight setting, and the core modules of LTGS, as shown in Figure 2.

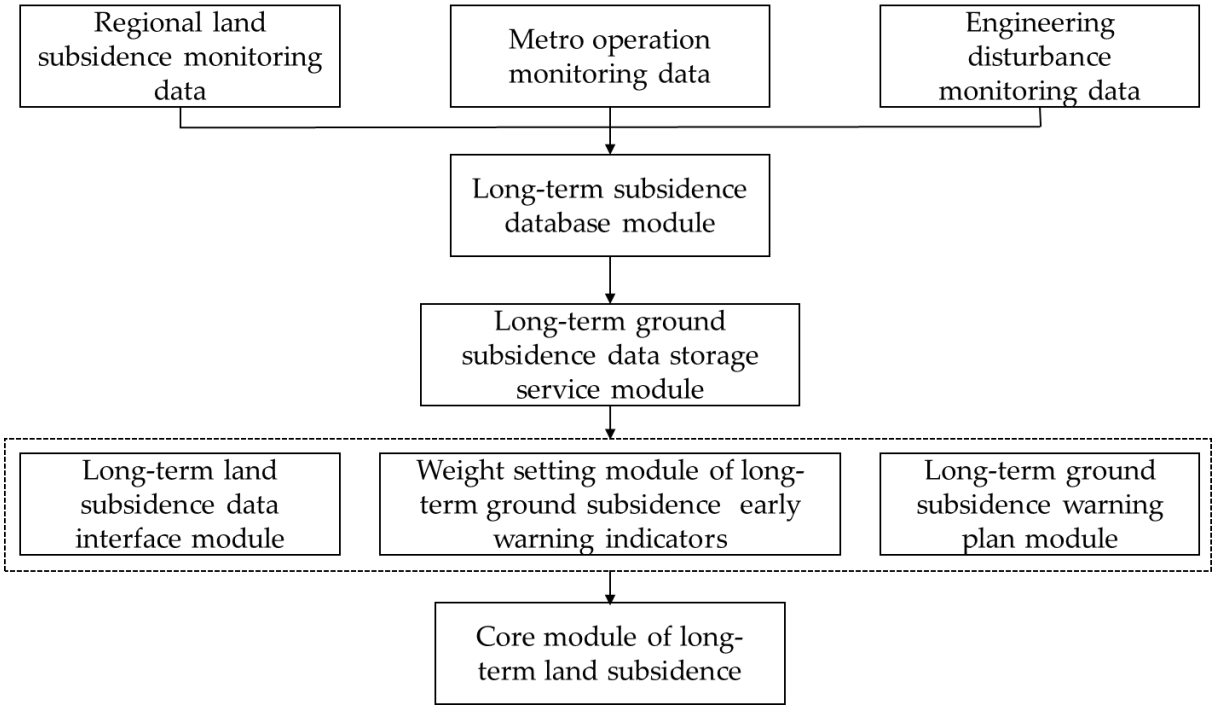

Figure 2. Software system modules.

The primary functions of each module in the software system are described as follows.

1. Database module of LTGS

The database module of LTGS is implemented using a lightweight SQLite database. This database primarily stores monitoring data related to regional ground subsidence, subway operation, and engineering disturbance.

2. Data storage service module of LTGS

The data storage service module of LTGS is achieved by defining a service category. It exhibits the functions of adding and querying LTGS data for the data interface, alarm–judgment–plan, and early warning indicator weight setting modules of LTGS. This module stores LTGS data in the database module through SQL statements.

3. Data interface module of LTGS

The data interface module of LTGS is achieved via DataInterfaceActivity, which includes the adding and updating of modules for LTGS monitoring locations. The updating module for LTGS can be accessed by clicking on the monitoring location number, allowing users to modify or delete the data associated with that location. In addition, data for the adding module of the LTGS monitoring point can be entered through the button "Add Subsidence data."

4. Alarm–judgment–plan module of LTGS

The alarm–judgment–plan module of LTGS is achieved via DataInterfaceActivity. The system interface displays three parameters: the monitoring location number, early warning value, and early warning levels of LTGS. This interface allows users to promptly assess the comprehensive early warning information for each location.

5. Early warning indicator weight setting module of LTGS

The early warning indicator weight setting module of LTGS is achieved via the weight setting of early warning indicators of LTGS, including maximum ground subsidence, maximum long-term subsidence rate, geological conditions, maximum tunnel subsidence, tunnel leakage degree, surface building intensity, and tunnel construction disturbance level.

6. Core module of LTGS

The entire system of the intelligent early warning and decision platform consists of the database module of LTGS. Four listeners are bound to each controller to transfer network data to the data storage service, data interface, and alarm–judgment–plan modules of LTGS. Users also have access to the data interface and early warning indicator weight setting modules of LTGS.

2.2. Overall Framework Structure of Software

Seven interfaces are designed to realize communication between users and the system, mainly including core interface, long-term subsidence early warning interface, early warning index weight setting interface, monitoring number list interface, adding subsidence data interface, updating subsidence data interface, and long-term subsidence help interface.

1. Core interface

The core interface includes four button controls, namely "early warning of long-term ground Subsidence during metro operation", "long-term ground Subsidence data during metro operation", "long-term ground Subsidence setting during metro operation", and "long-term ground Subsidence helps during metro operation".

2. Long-term ground subsidence warning interface

The list of long-term subsidence monitoring numbers, early warning values, and grades are displayed at the top of the interface. After the user clicks the "Start Alert" button at the bottom of the interface, the system will automatically alert each long-term subsidence monitoring point.

3. Alert indicator weight setting interface

The early warning indicator weight setting interface is mainly used to set the indicator weight. A total of seven early warning indicators are set, including the maximum ground subsidence, the maximum long-term subsidence rate, geological conditions, the maximum tunnel subsidence, the degree of tunnel leakage, the degree of surface building density, and

the degree of tunnel construction disturbance. Each early warning indicator corresponds to a text box. At the bottom of the interface, four buttons are available, namely "Update", "Return", "Default", and "Alert".

4. Monitoring number list interface

This interface mainly displays the list number of long-term ground subsidence monitoring points. Users can access it by clicking the "Long-term ground Subsidence data during metro operation" button in the core interface and then selecting the "Add Subsidence data" button at the bottom of the interface to enter the list interface for adding monitoring points. This list interface displays the data of multiple monitoring points. To delete a monitoring point in the monitoring number list interface, users can press and hold the monitoring point number to be deleted, and the "Delete" button will appear. Clicking on this button will delete the selected monitoring point number.

5. Add subsidence data interface

This interface displays the data of a certain long-term subsidence monitoring point. On the left side of the interface, the long-term subsidence early warning indicator names are listed, including the maximum ground subsidence, the maximum long-term subsidence rate, geological conditions, the maximum tunnel subsidence, the degree of tunnel leakage, the density of surface buildings, and the degree of tunnel construction disturbance. On the right side of the interface, corresponding text boxes display the values of the long-term subsidence early warning indicators. Users are required to enter the indicator values in the text boxes based on the actual measurements of the long-term land subsidence warning indicators.

6. Update subsidence data interface

In the monitoring number list interface, click on the existing monitoring point number to enter the subsidence update interface. The subsidence update interface closely resembles the subsidence addition interface, with the key distinction being that the long-term subsidence data stored in the database are now displayed in the text box on the right side of the update interface. Users can modify any data of long-term land subsidence in the interface according to their own needs.

7. Long-term ground subsidence help interface

The long-term ground subsidence help interface displays the input and modification of data within the intelligent early warning decision platform. It provides information on the early warning functionalities of the intelligent early warning decision platform and details the setting and principles governing its operation.

2.3. Data Processing

The atmospheric effect is identified as one of the most significant sources of error in this work. To mitigate these errors, a combination of GPS technology for precise coordinates and multi-scene image data is employed. In addition, azimuth filtering processing is applied to filter out non-overlapping parts of the main and auxiliary image spectra, while retaining their common Doppler spectral parts to enhance image coherence. The use of satellite precision orbit data and precise orbit ephemerides data is also implemented to eliminate systemic errors induced by orbital inaccuracies. These various data processing techniques collectively contribute to ensuring the integrity and purity of the collected data.

In this work, the initial phase of data processing involves a meticulous focus on the processing of satellite image data. At the master–slave image file polarization mode selection stage, master and slave images with the appropriate polarization are selectively chosen to form GIS Synthetic Aperture Radar (SAR) Single Look Complex (SLC) data pairs. During this selection process, it is imperative to input the reference Digital Elevation Model (DEM) file and the reference ellipsoid for subsequent alignment and terrain correction.

The interferogram is derived by computing the phase difference between the master and slave images, with the stripe variations in the interferogram serving as indicators

of surface deformation. Parameters such as distance-oriented view number, azimuth-oriented view number, and mapping resolution must be meticulously configured during interferogram generation, as these settings significantly impact the interferogram's quality and the accuracy of deformation extraction.

Post-interferogram generation, filtering and coherence calculation become imperative. The primary objective of filtering is the removal of noise and interference signals from the interferogram, enhancing the precision of deformation extraction. Coherence calculation is employed to assess the interferogram's quality and ascertain the reliability of deformation extraction. Various filtering methods and coherence calculation approaches can be selectively applied during these stages.

Subsequent to filtering and coherence calculation, essential processes including phase untangling, orbit refinement, and re-flattening are executed to optimize the sharpness of the interferogram and derive the deformation values within the study area. The outcomes of deformation extraction are typically presented in the form of a deformation map, providing a visual depiction of surface deformation distribution and magnitude. Additionally, the deformation results can be subjected to in-depth analysis and interpretation through integration with other geographic information data.

2.4. Implementation of DInSAR-GPS-GIS Technology

The data used is from Sentinel-series satellite data (https://scihub.copernicus.eu/ accessed on 10 May 2017). Based on the ENVI-SARscape platform, the process commenced with the utilization of multi-view data, which formed the foundational dataset for subsequent deformation analysis. This analysis was facilitated through an environmental satellite imagery platform and digital elevation model data. Subsequently, the study area underwent deformation monitoring using radar interferometric data. This data was calibrated and localized with the support of high-precision orbital data and GPS control points.

The selection of appropriate Ground Control Points (GCPs) emerged as a crucial step in the processing pipeline, ensuring the accuracy and reliability of the data. The GCPs played a pivotal role in the calibration and localization process. Coupled with the SAR SLC data pairs post-GIS precise position processing and radar interferometric processing, deformation maps with coordinated color schemes were generated in the DInSAR processing platform. These maps provided a visual representation of surface deformation within the study area.

In the final stages, utilizing tools such as ArcMap and other GIS software (pro2.0), subsidence deformation values were extracted and processed. This comprehensive approach offers essential decision support for various applications, including geological disaster early warning and urban planning. The entire processing workflow highlights the integrated application of DInSAR-GPS-GIS technology, delivering an efficient and accurate technical framework for surface deformation monitoring.

3. Early Warning Application

3.1. Project Background

The first phase of Hangzhou Metro Line 4 started its operation in 2015. The sections of CRS–CCS–JRS and XS–ERS–PS are selected as the research areas (Figure 3). The CRS–CCS–JRS section has three stations and two sections with a total line length of approximately 1.6 km. The surface buildings primarily include the Huacheng International Development Building, Gaode Landmark Plaza, Fortune Financial Center, and Hangzhou Qianjiang New City People's Center, Raffles City. The XS–ERS–Pengyu Station section consists of three stations and two sections with a total length of 1.7 km. The main surface buildings are the Hangzhou ERS and Mida Commercial Center, which are densely populated. The surface water system in the study area is mainly sourced from Xintang River, originating from Yaojiang Road and joining Qiantang River, eventually flowing into the canal along Fuchun Road to the northeast. Xintang River spans approximately 6 km in length, 10–25 m in width, and 2.0–3.5 m in depth, belonging to the Qiantang River water system.

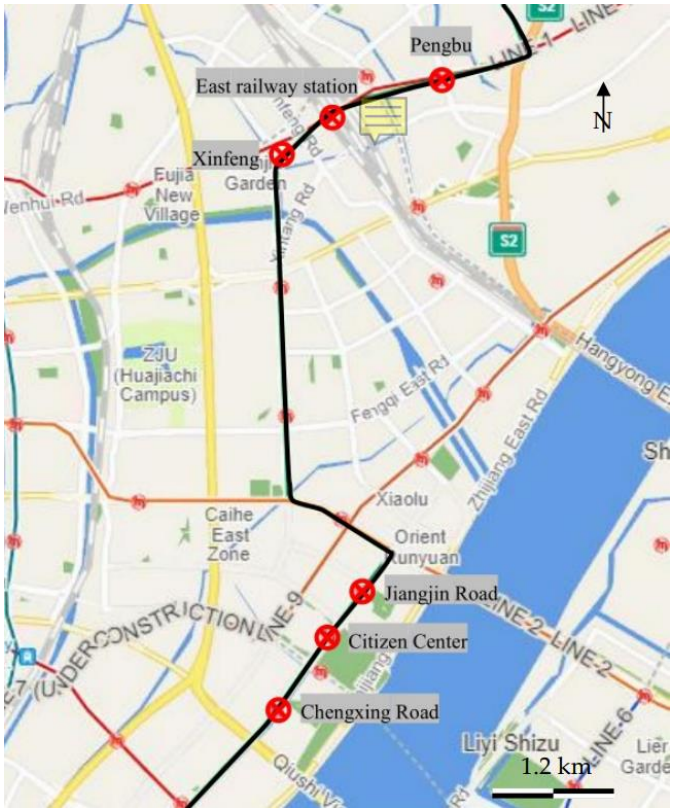

Figure 3. CRS–JRS and XS–Pengyu Station sections of Hangzhou Metro Line 4.

Figure 4 shows the partial typical longitudinal geological profile of the up-track. From Figure 4, the materials around the tunnel in the study area, from the shallowest to deepest layers, are largely composed of ① layers of miscellaneous fill, ③$_2$ layers of silty clay, ③$_3$ layers of clay silt with sandy silt, ③$_{52}$ layers of sandy silt with silt, ③$_7$ layers of clay silt with sandy silt, and ③$_{71}$ layers of silty sand silt.

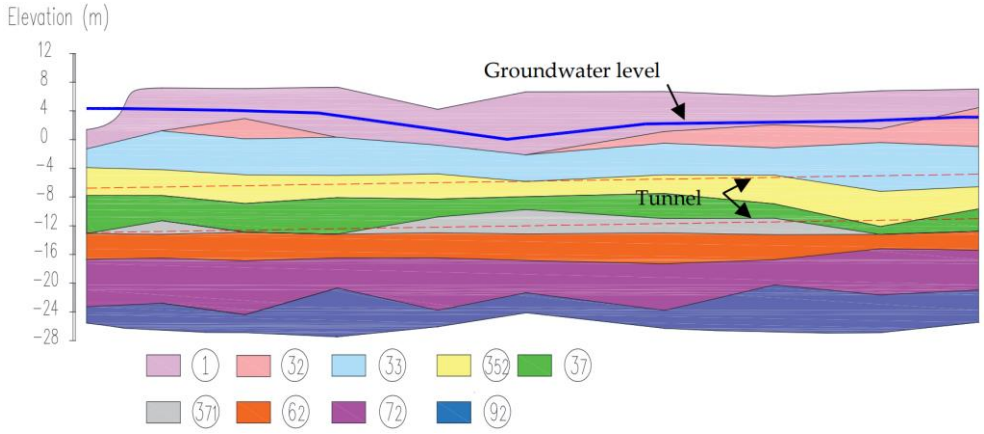

Figure 4. Partial typical longitudinal geological profile of the up-track.

The three layers of silty and sand are generally not dense. During engineering activities, engineering liquefaction hazards, such as sloping erosion, piping, and drifting sand under the action of groundwater hydrodynamic pressure, can easily occur.

The ⑥$_2$ layers under the bottom plate are mucky layers with poor properties. The bearing capacity of the foundation soil is 90 kPa, and the compression modulus is 3.8 MPa. Moreover, the material exhibits high compressibility, low bearing capacity, and poor engi-

neering performance. The materials under the ⑥$_2$ layers are largely composed of ⑦$_2$ silty clay and ⑨$_2$ silty clay, which are plastic and demonstrate good strength.

3.2. Project Background Collection of Early Warning Indicators of LTGS

3.2.1. DInSAR Ground Subsidence Monitoring Data

The main image of Sentinel-1A satellite monitoring data was selected on 27 May 2017, and the secondary image was taken on 28 January 2016 for 180 days. The intensity data of the main image were obtained after cutting the section of CRS–CCS–JRS of Hangzhou Metro Line 4 in the study area, as shown in Figure 5. The file name is

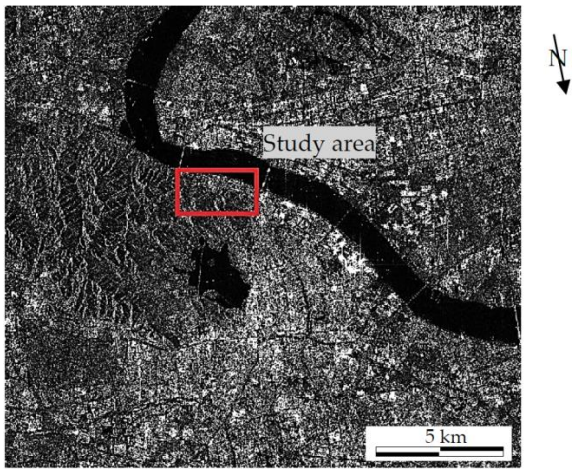

Figure 5. Intensity data of the main image after cutting.

sentinel1_69_20170527_100235174_IW_SIW1_A_VV_cut_slc_list_pwr.

The baseline estimate results show that the spatial baseline of the two scenarios is 23.103 m, which is considerably smaller than that of the critical baseline of 5812.323 m, and the time baseline is 180 days. The terrain change represented by a phase change period during DInSAR processing is 0.028 m.

Orbital refining and releveling treatment are performed on the study area, and 45 points are selected as the control points.

Phase transformation, the geocoding process, and deformation in the LOS direction of the study area are obtained. The resulting output file name is

sentinel1_69_20170527_100235174_IW_SIW1_A_VV_cut_slc_list_out_disp.

The interval deformation map of CRS–CCS–JRS in the study area is shown in Figure 6. The interval deformation map of XS–ERS–PS is shown in Figure 7.

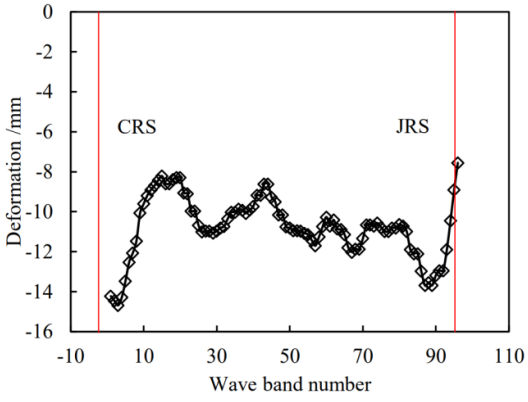

Figure 6. Deformation value of the study area in CRS–CCS–JRS.

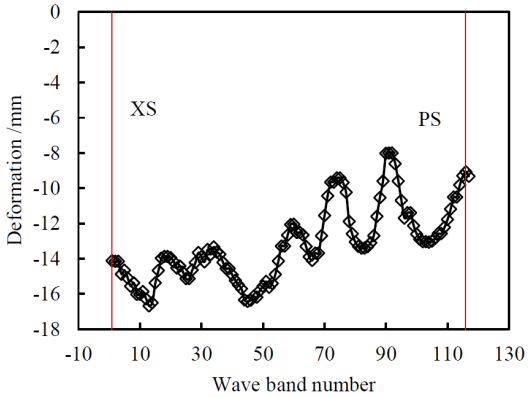

Figure 7. Deformation value of the study area in XS–ERS–PS.

From the preceding graphic analysis, the satellite image data from 27 May 2017, showed that the maximum subsidence in CRS–CCS–JRS is 14.68 mm, the minimum subsidence is 7.55 mm, and the average subsidence is 10.77 mm. Meanwhile, the maximum subsidence in XS–ERS–PS is 16.68 mm, the minimum subsidence is 8.00 mm, and the average subsidence is 13.17 mm.

3.2.2. Ground Subsidence Monitoring Data of Subway Operation

The monitoring of CRS–CCS started on 15 November 2016, and ended on 25 May 2017 (191 days). A total of 75 monitoring points in the left-line subway and 75 monitoring points in the right-line subway were found, which are shown in Figure 8a. The monitoring of the CCS–JRS intersection started on 15 November 2016, and ended on 17 May 2017 (183 days). A total of 64 monitoring points in the left-line subway and 63 monitoring points in the right-line subway were found, which are shown in Figure 8b. The monitoring of the XS–ERS intersection started on 19 November 2016, and ended on 26 April 2017 (158 days). A total of 55 monitoring points in the left-line subway and 56 monitoring points in the right-line subway were found, which are shown in Figure 8c. The monitoring of ERS–PS started from 19 November 2016 to 26 April 2017 (158 days). A total of 125 monitoring points in the left-line subway and 126 monitoring points in the right-line subway were found, which are shown in Figure 8d.

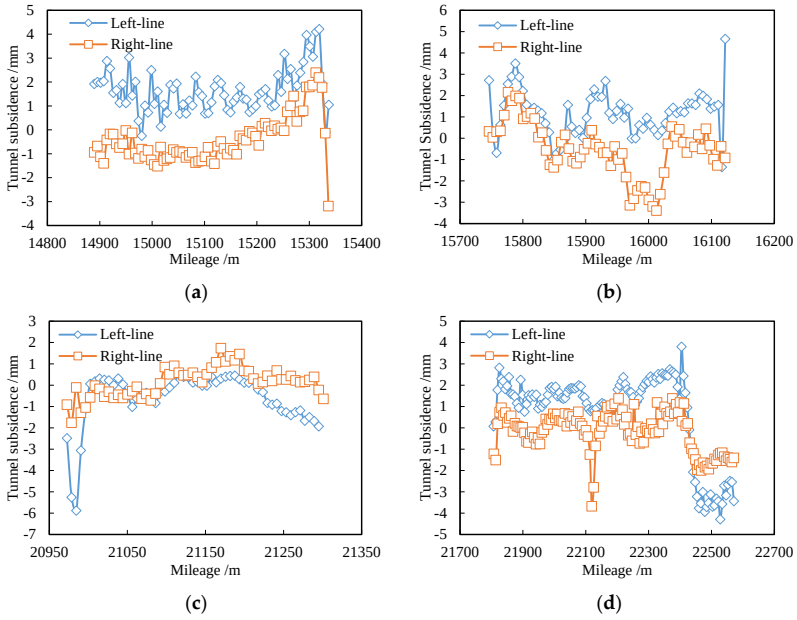

Figure 8. Monitoring of subsidence in different sections: (**a**) CRS-CCS; (**b**) CCS-JRS; (**c**) XS-ERS; and (**d**) ERS-PS.

The subsidence of the sections (CRS-CCS-JRS and XS-ERS-PS) in the study area are shown in Table 1.

Table 1. Subsidence values of the study area (Unit: mm).

No.	Section Name	Maximum Subsidence Value	Minimum Subsidence Value	Average Subsidence Value	Maximum Elevation Value	Minimum Elevation Value	Average Elevation Value
1	CRS-CCS left	−0.25	−0.11	−0.18	4.21	0.14	1.68
2	CRS-CCS right	−3.19	−0.03	−0.84	2.39	0.03	0.98
3	CCS-JRS left	−1.35	−0.003	−0.55	4.66	0.01	1.41
4	CCS-JRS right	−3.39	−0.18	−1.192	2.15	0.04	0.74
5	XS-ERS left	−5.881	−0.003	−1.227	0.509	0.035	0.255
6	XS-ERS right	−1.765	−0.026	−0.556	1.733	0.075	0.572
7	ERS-PS left	−4.291	−0.093	−3.026	3.804	0.282	1.646
8	ERS-PS right	−3.68	−0.031	−0.975	1.378	0.012	0.519

3.3. Early Warning Application of LTGS

The indicators of the integrated early warning system, based on the data collected from the early warning indicators of LTGS in the study area and related study [16], are listed in Table 2.

Table 2. Indicators of the early warning system for LTGS.

Early Warning System	Index System	Indicators (Unit)	Values	
			CRS-JRS (CJ001)	XS-PS (XP001)
Early warning index system for LTGS during subway operation in high-density urban areas	Regional ground subsidence	Maximum ground subsidence (mm)	14.68	16.68
		Maximum long-term subsidence rate (mm/d)	0.082	0.093
		Geological condition	Soft soil layer	Soft soil layer
	Metro operation indicators	Maximum tunnel subsidence (mm)	3.39	5.881
		Degree of tunnel leakage	Completely impermeable	Completely impermeable
	Engineering disturbance indicators	Density of surface buildings	Dense high-rise buildings	Dense multi-story buildings
		Degree of disturbance during tunnel construction	Disturbance range < 0.8 m	Disturbance range < 0.8 m

The early warning procedures in the CRS–JRS and XS–PS sections of Hangzhou Metro Line 4 based on the intelligent early warning and decision platform are expressed as follows.

(1) Access the core interface by clicking the "Early Warning of LTGS" APP file. Navigate to the monitoring number list interface of LTGS by clicking the "LTGS Data during Subway Operation" button on the core interface. Access the "Add Subsidence Data" interface by clicking the "Add Subsidence Data" button at the bottom of the interface. Input the monitoring number name CJ001 and the collected value of the warning indicator on the interface, then click the "Add" button to complete the input process of the early warning indicator value of LTGS. The monitor number list interface can be accessed by clicking the "Back" button.

(2) Return to the core interface from the monitoring number list interface, and then access the setting interface of warning indicators by clicking the "LTGS Setting during Subway Operation" button. Set the weight input for the early warning indicator on the interface. The warning indicator's weight setting can be completed by clicking the "Default" button at the bottom of the interface. Click the "Warning" button to return to the warning interface of LTGS.

(3) Click the "Start Early Warning" button on the warning interface of LTGS. During this period, the warning value and level of the CJ001 monitoring number are displayed in real-time. The early warning value is 2.31, and the early warning level is level 1, indicating a small risk.

The warning value of XS–PS (XP001) is 2.21, and the warning level is 1, indicating a small risk. Based on the preceding analysis, the warning level of LTGS for CRS–JRS and XS–PS of Hangzhou Metro Line 4 is Grade 1 indicating a small risk of LTGS.

4. Discussion

With the acceleration of urban construction, central cities have continued to extend toward the periphery, and an increasing number of subway lines are in operation. However, the long-term subsidence of operating metro tunnels affects ride comfort and safety. The operating environment of subways in high-density urban areas is complex, and there are many factors that affect long-term ground subsidence. Further research is needed to study the long-term ground subsidence characteristics in combination with various factors in different environments, and to establish multiple sets of warning indicators reflecting long-term ground subsidence during subway operation in high-density urban areas under different environments.

Given the time span limitation, the current study on long-term ground subsidence during subway operation primarily concentrates on the subsidence phenomenon and dynamic responses resulting from train vibrations, as well as the prediction of LTGS. This study, however, does not address the long-term ground subsidence induced by the reciprocating vibration of subway trains, lacking monitoring methods and early warning systems for such subsidence in high-density metro areas during subway operation. LTGS during subway operation should be investigated.

5. Conclusions

An intelligent early warning and decision platform is presented in this study. Software system modules were initiated, including database, data storage service, data interface, alarm–judgment–plan, early warning indicator weight setting, and core modules of LTGS. The overall framework of the software was constructed, and an intelligent early warning and decision platform with seven interfaces was developed to facilitate communication between users and systems.

Additionally, the study proposed an application method for the early warning of LTGS in high-density urban areas during subway operation. This method integrates the intelligent early warning decision-making platform, specifically the DInSAR land subsidence monitoring–operation subway subsidence monitoring coupling, applied to sections of the Hangzhou Metro Line 4 Phase I Project. The research revealed that the warning value of CRS–JRS is 2.31 mm with a warning level of Grade 1, indicating a low risk. Similarly, the warning value of XS–PS is 2.21 mm with a warning level of 1, signifying a small risk. These findings align with on-site conditions, confirming the effectiveness of the proposed method.

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