Application of D-InSAR technology in urban land subsidence measurement: A case study on Beihai city

X L Wang¹, J K You¹, L Hu¹, E L Qiu², J xiang³, K Guan¹ and C Xu¹

¹ School of Civil and Architecture Engineering, Nanchang Institute of Technology, 289 Tianxiang Road, Nanchang 330099, China
² Remote Sensing Center of Guangxi, 34 Jianzheng Road, Nanning 530023, China
³ Boyuanzhongce Testing Detection Technology Co., Ltd, Optical Valley Pharmaceutical Industrial Park, Wuhan 430206, China

Abstract. Land subsidence monitoring is of great significance for the city safety and development. D-InSAR technology is widely used in city ground subsidence monitoring as the development of synthetic aperture radar satellite applications, because of the surface deformation information in all-weather conditions with merits of large coverage, fast reaction and high accuracy. This paper studied and analyzed the land subsidence in Beihai by the track method of differential radar interferometry; the information of land subsidence was obtained. The distribution of land subsidence in Beihai city is widespread; the maximum land subsidence was 0.1567m in the studying area from 2001 to 2011, with the maximum annual average subsidence rate of 0.0157m/a, the most serious land subsidence point is located in E109°16′49.443″, N21°37′45.243″. Combined with the field investigation, ascertain the main influencing factors of land subsidence in Beihai city is the exploitation of groundwater resources. The result implies that the D-InSAR technology is remarkably effective on ground subsidence monitoring in Beihai, which can accurately extract the information of ground deformation area.

1. Introduction
Land subsidence is caused by natural and man-made common factor, which appears macroscopically as a decrease in ground elevation and microscopically as a slow-changing geological phenomenon in the compression of soil within the stratum[1]. It is an unrecoverable and permanent loss of environment and resources, which can even become a geological disaster. Land subsidence is a worldwide geo-environmental problem, which is encountered in the process of urbanization. It has great influence on the sustainable development of social economy and has attracted widespread attention from society and scholars in recent years[2]. The land subsidence in China is mainly concentrated in economically developed areas, such as the Yangtze River Delta, the North China Plain, the Songliao Plain, and southeast coastal plains, while there is a lack of research on the land subsidence of the newly emerging urban agglomerations which are in rapid development[3]. As the core city of economic development in the northern gulf urban agglomerations, Beihai is a cloudy and rainy area in the south, and its urban geo-environmental problems are more prominent. At present, Beihai City only focuses on five types of geo-environmental problems, such as seawater intrusion, landslides, land surface collapse, ground fissures and collapses, while there are few concerns about the geo-environmental problems of land subsidence that occurred in the 90s of last century. Therefore, it is necessary to study and control urban land subsidence in Beihai City, to discuss its spatial
distribution and evolution characteristics and reduce the economic losses and casualties caused by such disasters. Differential Interferometry Synthetic Aperture Radar (D-InSAR) is a kind of space geodetic technique developed rapidly in recent years. It can obtain high-precision information of surface deformation all-weather, wide range and fast. In recent years, D-InSAR technique has been widely used in earth sciences, environmental sciences, and many other fields such as the monitoring of earthquakes, glacial movement, land subsidence, landslide and other geological disasters[4].

2. Research area survey and technical methods

2.1. General situation of research area
The research area is a Mesozoic fault depression basin, which is located in Beihai City, the southern end of Guangxi Zhuang minority Autonomous Region and the northeast shore of the Northern Gulf Economic Zone. Beihai City is an offshore subsidence basin which belongs to marine deposition low terrace. The soil is mainly sandy soil with high water content, and it is prone to land subsidence. At present, land subsidence occurs in Beihai City, southern part of Qinzhou, and southeast of Fangchenggang. The land subsidence of the Baijin villa community in Beihai City has reached more than 10cm since the beginning of construction, which causes cracks and suspensions of houses, cracks of windows evidently.

2.2. Data resources
Beihai City is a cloudy and rainy area with high vegetation coverage. According to the meteorological and geological features of Beihai City, ALOS PALSAR image with relatively longer wavelength \( \lambda = 23.5\, \text{cm} \) is selected as the image data of land subsidence study. As shown in Table 1, PALSAR is an L-band synthetic aperture radar sensor carried by the ALOS satellite, which is not affected by cloud layer, weather and day and night. PALSAR can observe the earth all-weather and obtain the data of three kinds of observation modes: high-resolution, scanning synthetic aperture radar and polarization.

The DEM (2001) data of SRTM3 jointly measured by NASA and NIMA was selected in this study. The accuracy of the elevation is 10 m and the absolute accuracy is \( \pm 16 \).

| No. | Date       | Format | Type of data |
|-----|------------|--------|--------------|
| 1   | 20110106   | FBS    | Level 1.1    |
| 2   | 20110221   | FBS    | Level 1.1    |

2.3. Technical and methods
The Differential interferometry with two rails method is mainly used to monitor ground subsidence in this paper. Interferograms are generated according to two scenes of SAR images before and after land subsidence occurs in the study area. The topographic phase of the area is simulated with the external DEM data, which is removed from the interferogram to obtain the land subsidence phase of the study area.

In view of the characteristics of cloudy and rainy areas in the south, the noise of radar data needs to be effectively removed. Based on this, the optimal approaches to the measurement of ground subsidence by the interference of differential radar in Beihai area are studied in this paper:

- The multi-view processing of single radar image is adopted to remove systematic speckle noise, as shown in Figure 1.
- Repeat track data correction to correct deviation of the two images in the azimuth and distance upward in size, direction and incidence angle during the measurement process.
- Baseline optimization of the two polynomial is used to estimate the corrected image pairs, and image pairs whose vertical baseline is less than the critical baseline are interfered.
- We selected the most optimized Goldstein filtering method and determined the MCF unwrapping technique by analyzing the current filtering and unwrapping methods.
Fig 1. Comparison diagram of the effect before and after the filtering (left is the original image, the right is the filtered image).

From Figure 1, it can be seen that before the multi-view processing, there are speckle noises in the SLC images. The speckle of the multi-view filtered images are obviously reduced after multi-view filtering and the images are clearer, so multi-view filtering removes the speckle noise of the SLC images well.

The interferograms after processing have the disadvantages of low signal-to-noise ratio and unobvious period, which will affect the phase unwrapping, the accuracy of the DEM digital elevation model, and the accuracy of the land subsidence. In order to ensure the same image resolution while suppressing noise, the interferogram filtering must be used. In this paper, by comparing the current main filtering methods—Adaptive, Boxcar and Goldstein—we obtained the best equivalence of Goldstein filtering. As shown in Table 2. Phase unwrapping is a method that restores the main phase value or phase difference value to a true value, as a process to restore the best information, it is extremely important in this study. Through the statistical comparison among the regional growth method, the minimal cost flow method and the MCF method provided by the ENVIsarscape module, it is found that the standard deviation of the MCF method is 0.878566, which is smaller than the regional growth method and the minimum cost flow method. Therefore, MCF method is used for unwrapping in this paper.

| image                  | average | Relative standard deviation | equivalent number of looks |
|------------------------|---------|----------------------------|---------------------------|
| Original image         | 0.61    | 2.63                       | 0.054                     |
| Adaptive filter        | 0.83    | 1.80                       | 0.213                     |
| Boxcar filter          | 0.97    | 1.42                       | 0.467                     |
| Goldstein filter       | 1.02    | 1.29                       | 0.625                     |

After the phase-unwrapped processing, the phase main value of the interferogram has been converted into a real phase value. In combination with the inversion phase of the external DEM, the subsidence information of each pixel can be calculated and geocoded, which is converted from a slant range projection to a geographic coordinate projection to obtain a land subsidence map.

3. Results and analysis

3.1 Spatial Distribution characteristics of Land subsidence in Beihai City
The data of Beihai City in 2011 was analyzed by the Differential interferometry with two rails method to obtain the spatial distribution of ground deformation, as shown in Figure 2. Land subsidence in the study area occurred in five regions: southwest, northwest, central, northeast, and southeast. The subsidence being more serious in the center, and a small portion of the northeast and southeast uplift. The specific performance is that the ground deformation is in the three districts and one county under the jurisdiction of Beihai City: Deformation of the ground in the southwest of the city occurs in urban
area, especially in the old urban area of Beihai City; there are large-scale land subsidence areas in Xichang Town, Wujia Town, and Shiwan Town in the northwest of Beihai City; significant land subsidence occurs in the central region such as Fucheng Town, Hepu County, Lianzhou Town and other areas; the land subsidence area in the northeast appears in Zhakou Town, where a large number of land subsidence points are distributed; the land subsidence in southeast appears in Xingang Town and Nankang Town and other areas. It can be seen that land subsidence mainly occurs in the urban areas of Beihai and its surrounding towns, and attention must be paid to land subsidence in urban planning and construction so as to avoid economic losses.

It can be seen from Table 3 that the maximum figure of land subsidence in Beihai City is 0.1567 m during the period of 2001 to 2003, the maximum annual average land subsidence rate is 0.0157 m/a. The most serious land subsidence is located in 109°16′49.443′′E, 21°37′45.243′′N where some parts of the region are slightly uplifting, and the maximum uplift is 0.2498m. The surface deformation in study area is divided according to the spatial analysis module and it can be found that the subsidence area of the study area reached 628.42Km², accounting for 26.24% of the total proportion. The area of no subsidence is 1650.53 Km² and the surface uplifted area is 115.90 Km², so the situation of land subsidence is rather severe.

| Subsidence level | Land subsidence value (m) | Surface change area (Km²) | Proportion (%) |
|------------------|---------------------------|---------------------------|----------------|
| Subsidence area  | -0.1567 to -0.0126        | 236.64                    | 9.88           |
| Normal area      | -0.0126 to 0.0062         | 391.78                    | 16.36          |
| Uplifted area    | +0.0062 to +0.01338       | 1650.53                   | 68.92          |
|                  | +0.01338 to +0.1139       | 112.32                    | 4.69           |
|                  | +0.1139 to +0.2498        | 3.58                      | 0.15           |

3.2 causes of land subsidence in Beihai City
Many studies at home and abroad have shown that the factors that induce land subsidence are[5]: neotectonic movement, soil consolidation, exploitation of underground resources, sea level rise and urban construction, and the most important factor is the overexploitation of underground fluid or solid minerals. The average annual water resources in Beihai City is 4.05 billion m³, and the per capita occupancy is less than 2,900 m³, slightly higher than the national average and lower than the average level in the whole region (about 4000 m³) [6]. According to the Guangxi Water Conservancy department’s Water Conservancy Bulletin in 1999, the main rivers in southern, such as the Nanliujiang River and the Qinjiang River, were all IV - V class water and basically lost their functions as drinking water sources. Beihai City is rich in groundwater resources where Hepu Basin and Nankang Basin are just like natural underground water reservoirs. Therefore, the drinking water problem in Beihai City has turned to the exploitation of groundwater resources. With the continuous development of the
economy, and the continuous increase of the gross national product, the secondary industry continues to develop, the intensity of groundwater exploitation has been greatly strengthened. According to the first National Water Conservancy Survey in 2011, there are 153,426 wells with different kinds of types for water extraction in Beihai City. Groundwater exploitation amounted to 129.41 million m$^3$, of which 3,573 wells in Haicheng District with 18.07 million m$^3$, 13,668 wells in Yinhai District with 58.14 million m$^3$, 18,225 wells in Tieshan Port with 11.37 million m$^3$ and 117,959 wells in Hepu County with 41.83 million m$^3$. At present, there are 5 water sources in Beihai City, among which the wells in the water source of Hetang Village in Xitang Town, Yinhai District, and Houtang Village in Haicheng District are concentrated. The other three water sources are: Longtan Village, Xitang Town, Yinhai District; Gaoyang Village, Haicheng District; Sanjia Village, Zhakou Town, Hepu County, where the exploitation of groundwater resources is sporadic. In order to study the correlation between groundwater exploitation and land subsidence, the distribution of groundwater water source sites is integrated with the land subsidence distribution area. Figure 3 shows the relationship between groundwater source and land subsidence. The results show that even ground subsidence occurs in groundwater sources. Therefore, it is concluded that there is a positive correlation between land subsidence and groundwater overexploitation in the study area. The area of ground subsidence caused by underground mining in Shanxi Province is more than 520 km$^2$, and the land subsidence area of Kaiyu mining region in Hebei amounts to 290 km$^2$[7]. Obviously the problem of ground subsidence caused by mining has a long history. The surface collapse and deep pit of Shijiao Village in Zhakou Township, Hepu County is obvious, and the phenomenon of house cracking is serious. The reason for this phenomenon was that groundwater was pumped up during the mining process in large-scale quarries of the region so as to prevent stone pits from ponding. It can be seen that the man-made factors of urban land subsidence in Beihai are mainly the exploitation of groundwater resources and mining.

The rising sea level in coastal area is another contributing factor to land subsidence. According to research by Liu Yong and others[8], the relative increase in sea level in the Yellow River Delta is basically the amount of land subsidence in its coastal area. According to the statistics of the State Oceanic Administration's Sea Level Bulletin, Guangxi's sea level showed a significant rising trend in recent 40 years, and the rising rate is about 0.0029 cm/a. According to the above research, the average annual maximum subsidence rate in Beihai from 2001 to 2011 is 0.0157 m/a. The contribution rate of sea level rise to land subsidence is 0.23%, which has little effect on land subsidence in Beihai City.

The above analysis shows that using the D-InSAR with two rails method can effectively monitor the urban land subsidence in cloudy and rainy south areas and obtain high-resolution surface subsidence information. Based on this, the spatial distribution characteristics of land subsidence in the region are analyzed to discuss causes of formation of land subsidence.

4. Conclusions

In this paper, based on spaceborne synthetic aperture radar data, D-InSAR technology was used to monitor and study land subsidence in Beihai City, the amount of land subsidence in Beihai City from 2001 to 2011 was quantitatively analyzed, and the factors that causing land subsidence in Beihai City was analyzed. The following conclusions are drawn:

- The maximum value of land subsidence in the study area of Beihai City during 2001-2011 is 0.1567 m, and the maximum annual land subsidence rate is 0.0157 m/a.
- The land subsidence in Beihai City in 2001-2011 mainly occurred in five regions: southwest, northwest, central, northeast, and southeast, and the worst subsidence situation is in the central region. Land subsidence in the southwest of the city occurs in Beihai City, especially in the old urban area of Beihai City; there are large-scale land subsidence areas in Xichang Town, Wujia Town, and Shiwan Town in the northwest of Beihai City; the significant area of land subsidence in the central appears in the Fucheng Town, Hepu County, Lianzhou Town and other areas; the land subsidence area in the northeast appears in Zhakou Town, where a large
number of land subsidence points are distributed; the land subsidence in southeast appears in Xingang Town and Nankang Town and other areas.

- The main influencing factors of land subsidence in Beihai City are the exploitation of groundwater and the exploitation of solid minerals. The impact of rising sea level on the land subsidence in Beihai is relatively small.

Acknowledgments
This study was supported by Jiangxi Provincial Education Department (GJJ170978); Natural Science Foundation of China (NO.51568048); Natural Science Foundation of Jiangxi provincial Science and Technology Department (20161BAB216109); University Students Innovation and Entrepreneurship Training Program of China (2016020); 2018 University Students Innovation and Entrepreneurship Training Program of Nanchang Institute of Technology.

References
[1] Xue Y, Zhang Y, Ye S J and Li Q F 2003 Land subsidence in China and its problems Quaternary Study. 23 (6) 585–93
Zheng X X, Wu Q, Ying Y F, Xie X C and Hou Y S 2002 Problems on land subsidence in China's coastal areas in the 21st century and their solutions Science and Technology Review. 20 (29) 47–50
[2] Guo H P, Bai J B , Zhang Y Q, Wang L Y, Shi J S, Li W P , Zhang Z C , Wang Y L, Zhu J Y and Wang H G 2017 The evolution characteristics and mechanism of the land subsidence in typical areas of the North China Plain Geology in China. 44(6) 1115–27
Yuan M, Bai J W and Qin Y k 2016 A review on land subsidence research Journal of Suzhou University of Science and Technology. Nat sci. 33(1) 1–5
[3] Liu Y 2001 Land subsidence research approaches and advent problems Earth Science Frontiers. 8 (2) 273–8
[4] Cheng X, Li X W, Shao Y and Li Z 2006 Study on remote sensing of DINSAR glacier movement in the Grove Mountains, Antarctica China Science Bulletin. 51 (17) 2060–7
Zhou C X, Deng F H, Ai S T, Wang Z M and E D C 2014 Determination of ice-flow velocity at the polar record glacier and dalk glacier using dinsar Geomatics and Information Science of Wuhan University. 39(8) 940–4
Meng Q K, Wang B C and Miao F 2016 Research on Monitoring the ground subsidence in mountainous city by SBAS-InSAR—a case study in Panzhihua city Science Technology and Engineering. 16(13) 12–17
[5] Zhang J, Hu G D and Luo N B 2006 Landslide monitoring by INSAR technology Chinese Journal of Engineering Geophysics. 1 (2) 147–53
Teatini P, Tosi L, Strozzi T, Carbognin L, Wegmüller U and Rizzetto F 2005 Mapping regional land displacements in the Venice coastland by an integrated monitoring system Remote Sensing of Environment. 98(4) 403–13
Tosi L, Teatini P, Carbognin L and Brancolini G 2009 Using high resolution data to reveal depth—dependent mechanisms that drive land subsidence: the Venice coast Italy. Tectonophysics. 474(1) 271–84
[6] Qian X E, Ou Y C and Wu S B 2004 Focus on water resources in Beihai city South Land Resources. (6) 14–15+18
[7] Chang Z Q and Gong H L 2011 Analysis and prospect on the prediction methods of ground subsidence in mining area Journal of Geo-Information Science. 13(2) 151–6
[8] Liu Y 2013 Spatio temporal evolution of land subsidence and mechanism discussion in the Yellow River Delta, Qingdao University of Chinese Academy of Sciences.Institute of Oceanography