STUDY ON THE SPATIAL-TEMPORAL EVOLUTION OF SUBSIDENCE IN THE BEIBU GULF REGION BY TIME-SERIES INSAR

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ABSTRACT:

In this paper, based on the 24 scenes Sentinel-1A images covering the Beibu Gulf region from 2018 to 2020, we used the PSInSAR technique to obtain the surface subsidence information in the study area and analyzed the surface subsidence spatial-temporal characteristics. The results showed that (1) The subsidence rate of most subsidence areas in Beibu Gulf is from -10.0mm/year to -1.1mm/year. And most of the subsidence areas are located in the coastal areas in the south of the study area. The distribution was obvious, and the maximum subsidence rate can reach -17.2 mm/a. However, the subsidence areas of villages and towns located in Qinzhou in the north and inland of the study area are relatively stable. (2) Subsidence was mainly concentrated in Yinhai District, Haicheng District, Tieshan Port District and Fangcheng District of Fangchenggang in Beihai City. The annual average Subsidence range from -10.0mm/year to -1.1mm/year. Among them, the Tieshan Port area and Fangcheng District had obvious subsidence trends, with the maximum cumulative subsidence reaching -35.9mm. (3) The spatial-temporal characteristics of wide-area surface subsidence and the relationship between surface subsidence and influencing factors in the Beibu Gulf region were determined.

1. INTRODUCTION

Surface subsidence is a kind of surface deformation phenomenon caused by human or natural factors. Serious subsidence will directly lead to major safety accidents(e.g., house collapse). It has a great impact on people's normal life and economic development (Qin et al., 2019; Bai et al., 2017). Therefore, its monitoring can effectively prevent disasters caused by surface subsidence. Traditional subsidence monitoring (e.g., level survey, GNSS, etc.) cannot guarantee the timeliness and large area monitoring (Poland et al., 2006), while interferometric synthetic aperture radar (InSAR) technique, with the advantages of all-day, all-weather, wide coverage area and high spatial-temporal resolution, makes it possible to monitor the surface on a large scale.

Differential interferometry synthetic aperture radar (DInSAR) can detect sub-cm surface subsidence, but it is susceptible to temporal and spatial decoherence and atmospheric delay, which makes it difficult to accomplish high-accuracy long-interval surface monitoring (Gabriel et al., 1989; Dong et al., 2013). Therefore, the time-series InSAR method evolved with time development, and the permanent scatterer InSAR (PSInSAR) technique was proposed (Ferretti et al., 2001), which can quickly and accurately obtain the vertical deformation field of the region. In urban or sparse vegetation areas, mm or even sub-mm surface deformation can be obtained, which effectively solves the problems of time, spatial decoherence, and atmospheric effects, which limit the measurement accuracy in DInSAR technique. Subsequently, a technique to improve the traditional PS algorithm has been proposed (Hooper et al., 2006), using amplitude discrete features and interference phase space correlation features to identify PS points. This method can also obtain the surface deformation of time series in mountainous areas, making the application of PS technique more extensive. It is not only limited to flat areas, but also gradually to mining areas, tracks, landslides, and dams. In order to prevent hidden dangers, countermeasures are made in advance. (Li et al., 2021).

In recent years, many domestic scholars have used this technique to carry out relevant research in several cities in China. For example, Liu et al. (2019) used Sentinel-1 data to monitor the deformation information of Foshan City from June 2015 to September 2018. They observed the subsidence of the Foshan City subway line using the improved PSInSAR technique, which provided a reference for the study of subsidence changes along the subway line. Zhou et al. (2021) used PSInSAR technique to process and analyze 35 Sentinel-1A images from 2018 to 2020 in the Shanghai area. They obtained the cumulative subsidence and subsidence rate field of the area and infrastructure. Although this technique is widely used in several cities in China (Lei et al., 2013; Bai et al., 2017), there are relatively few studies related to ground subsidence monitoring in the Beibu Gulf region.

Therefore, this study focuses on the land subsidence in the Beibu Gulf area and uses the 24 sentinel-1A images sets of the coverage area from 2018 to 2020 for PSInSAR data processing. Through the identification of the amplitude deviation difference index and coherence coefficient, PS points with high coherence are selected to obtain the subsidence time series and subsidence rate information for subsidence monitoring in the study area, to analyze the characteristics and causes of land subsidence in the area.

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2. STUDY AREA AND DATA SOURCE

2.1 Study area

The Beibu Gulf is located in the south of the Guangxi Zhuang Autonomous Region, including the coastal parts of Fangchenggang, Qinzhou, and Beihai. The area is approximately 164.82 km long and 69.71 km wide, with longitude ranging from 107°95′E to 109°92′E and latitude ranging from 21°29′N to 22°01′N. The topography of the study area is high in the northwest and low in the southeast.

The Beibu Gulf is located at the edge of the South China plate, and its evolution process has experienced two stages: rift and depression. However, the process is complex, resulting in different degrees of depression in the basin. The basin in this region is rich in oil and gas reserves and is surrounded by harbors and bays, each with ports and abundant resources (Hu et al., 2011; Lin et al., 2015). The economic activities are mainly port trade, fishing in the sea, resource extraction, etc. As of 2018, the resident population of Qinzhou, Beihai and Fangchenggang reached 5,485,900 people. The red box in Figure 1 represents the research area of this paper, including Fangchenggang, Qinzhou, and Beihai. Figure 2 shows the backscattered intensity images of Sentinel-1A SAR images covering the region.
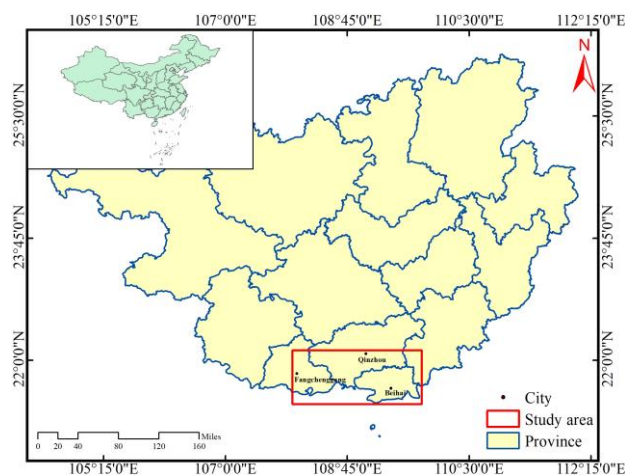

Figure 1. The study area is in the red box, and the bottom map is the boundary map of Guangxi municipalities.
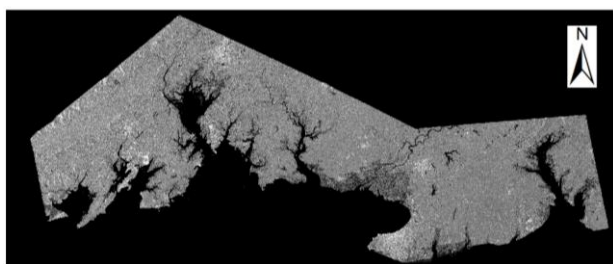

Figure 2. Sentinel-1A SAR intensity map of the study area.

2.2 Data sources

The 24 ascending SAR images used in this paper are from Sentinel-1A launched by the European Space Agency (ESA) the satellite carries C-band synthetic aperture radar antenna with a 12-day revisit cycle. The imaging time span is from September 2018 to July 2020. The incident angle of the image center is 34.5°, and all SAR images modes are VV. The specific parameters of sentinel-1A are shown in Table 1. Terrain phase

removal was performed using STRM-3 DEM data from the space shuttle radar terrain observation mission (SRTM) at 90m resolution provided by NASA to improve the accuracy of the results. We used the precise orbit data published by ESA to perform orbit refinement and phase re-flattening for all image data.

SAR type	Parameters
Satellite model	Sentinel-1A
Imaging mode	IW
Revisit cycle	12 days
Band	C
Polarization mode	VV
Time span	September 2018－July 2020
Central incidence angle on the test site	34.5°
Range resolution	1.2m
Azimuth resolution	13.9m

Table 1. Specific parameters of Sentinel-1A SAR

3. METHODOLOGY

To focus on the time and space de-correlation problems and the effects of atmospheric effects in the application of DInSAR technique. This paper used PSInSAR technique for data processing. The technique overcomes or reduces the de-coherence problems and atmospheric delay through point targets with a stable phase and achieves a high-precision measurement of the time-series surface deformation, thereby enabling the researcher to obtain more reliable surface deformation results.

The principle of PSInSAR technique is to use multiple SAR images covering the same area. Through statistical analysis of the stability of amplitude and phase information in time series, stable target points that are not affected by temporal and spatial baseline de-correlation are detected. Based on the phase time series of these target points, modeling and analysis are carried out to obtain high-precision deformation monitoring results. In this paper, based on sarscape software, we use PSInSAR technique to process 24 sentinel-1a SAR images in the study area. We have received the surface subsidence rate in Beibu Gulf. The technical process is shown in Figure 3, and the data processing process is as follows.

(1) All SAR images are arranged according to time series and calculated comprehensively combined with three different factors, such as spatio-temporal baseline and Doppler centroid frequency difference. In this paper, the images on July 10, 2019 was selected as the main image, and the other secondary images are registered and resampled to the master image. We set the time baseline and space baseline thresholds to 360d and 101m, respectively, as shown in Figure 4.
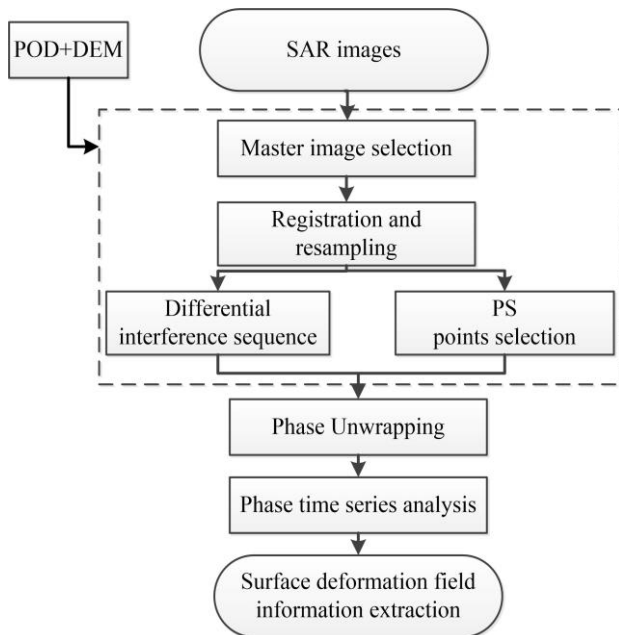
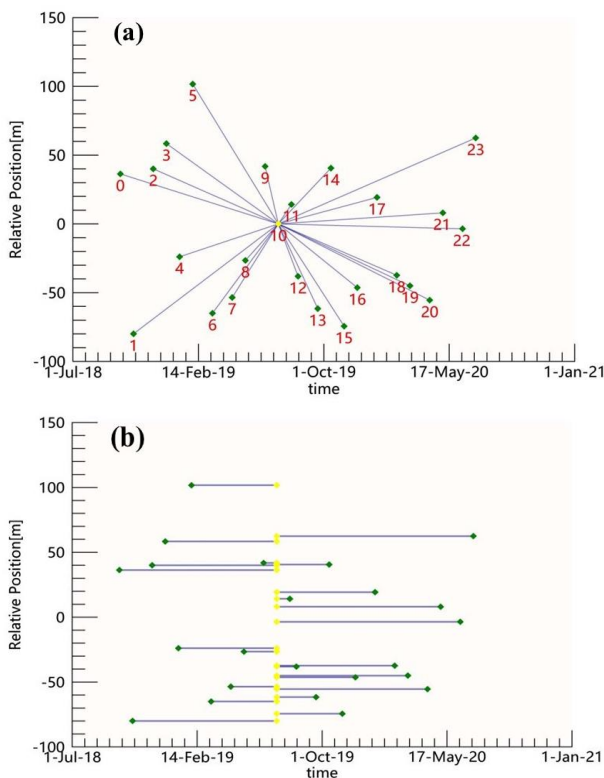Figure 3. Flow chart of PSInSAR technique

Figure 4. (a) Time-position of Sentinel-1A image interferometric pairs; and (b) time-baseline of image interferometric pairs. The blue lines depict interferometric pairs. The yellow and green diamonds correspond to the master image and secondary images, respectively.

(2) The other secondary images are registered with the master image. After differential interference processing, the differential interference phase is obtained.

$$\varphi = \varphi_{def} + \varphi_{orbit} + \varphi_{atm} + \varphi_{dem} + \varphi_{noise} \qquad (1)$$

where φ_{def} represents the phase of deformation in the LOS direction, φ_{atm} refers to the phase generated by atmospheric effects, φ_{orbit} indicates the phase generated by orbital errors, φ_{dem} denotes the phase generated by DEM errors, and φ_{noise} denotes the phase generated by noise. The phase caused by the DEM can be eliminated by an external reference DEM, and a more stable PS point can reduce the effect of φ_{noise}.

(3) In this paper, the amplitude deviation index is used to select PS candidate points with high coherence. Based on these PS candidate points, the relationship is established by Delaunay irregular triangulation. Then the phase information is unwrapped, and the unwrapped differential phase is classified to eliminate the phase error.

(4) We used the frequency characteristics of the time domain and space domain to separate the linear deformation and DEM error. The residual phase is filtered by a high-pass filter in the time domain and a low-pass filter in the space domain. Finally, the atmospheric phase and nonlinear deformation estimates of each differential interferogram are obtained.

(5) The nonlinear deformation and linear deformation are summed to obtain the deformation rate field in the study area.

4. RESULT ANALYSIS

4.1 Analysis of subsidence rate in the study area

After the above PSInSAR technique processing, we obtained the subsidence rate map in the Los direction (positive near the radar line of sight and negative away from the radar line of sight) in the Beibu Gulf from September 2018 to July 2020. The total number of PS points extracted from the Sentinel-1A Tops datas reached 1961188. From the inversion results in Figure 5. Generally speaking, the subsidence rate of most subsidence areas in the Beibu Gulf from -10.0mm/year to -1.1mm/year. And most of the subsidence range is located in the south of the study area, mainly in coastal areas, which are widely distributed. From the analysis of the Beibu Gulf Urban Agglomeration, there are two obvious subsidence areas. They are distributed in the coastal areas of Beihai and Fangchenggang respectively. The subsidence rate in the subsidence area is mostly between -4.2 and -10.0mm/a. The annual average maximum subsidence rate can reach -17.2mm/a. While the subsidence in Qinzhou and the inland townships located in the north of the study area is relatively stable, there is no obvious subsidence on the surface trend, and there is a relatively small uplift.
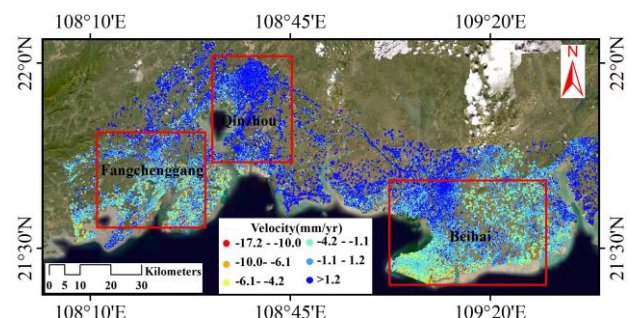

Figure 5. Subsidence rate distribution in the study area
Inside the red rectangle are the three urban agglomerations in the Beibu Gulf region. (i.e., Beihai, Fangchenggang, and Qinzhou).

4.2 Spatio-temporal analysis of surface subsidence in the study area

In order to better analyze the spatial and temporal characteristics of the subsidence field in the Beibu Gulf region, this paper focuses on the subsidence mechanism analysis of Beihai City and Fangchenggang according to the subsidence rate distribution in the study area. Four feature areas (S1, S2, S3 and S4) in the study area were selected for the subsidence time series analysis. The time series points PS1-PS4 are extracted in each feature region respectively. The spatial distribution of the characteristic area and the time series points of each area are shown in Figures. 6 and 7, and the accumulated subsidence of the time series points is shown in Figure. 8 (the time series points are in the red triangle shape in Figure. 7).

It is shown by the subsidence rate distribution map of the Beihai area (Figure. 6a) and the Fangchenggang area (Figure. 6b). The subsidence areas are mainly concentrated in the four areas of Yinhai district, Haicheng district, Tieshangang district and Port district in the southern coastal area, and the surface subsidence is more obvious compared with other areas. Among them, the coastal areas of Yinhai District and Haicheng District show a wide range of subsidence with a slow subsidence trend, and the maximum cumulative subsidence in Yinhai District and Haicheng District reaches -20.2mm/a and -14.8mm/a, respectively.

S3 is located in the Tieshan Port area in the eastern part of Beihai City. The maximum accumulated subsidence in this area can reach -34.5mm, and the subsidence is obvious. According to data display, this area is a coastal industrial zone, with a variety of industrial parks coexisting. It is also known as the "100 million tons port". The total industrial output value accounts for 53.86% of the city, becoming the first 100 billions yuan output value park in Beihai. While the Tieshan Port East and West Harbor will achieve full coverage of 100,000 tons ship navigation. It is expected that by 2030 the port throughput capacity of Tieshan Port will exceed 100 million tons.

The surface of S4 is located in the port area along the south coast of Fangchenggang, where an obvious subsidence funnel occurs locally. The surface subsidence shows a continuous sinking trend, with maximum accumulated subsidence of up to 35.9mm.
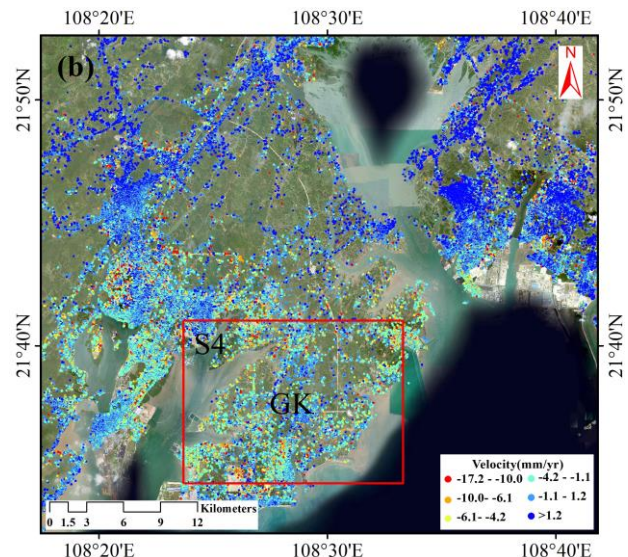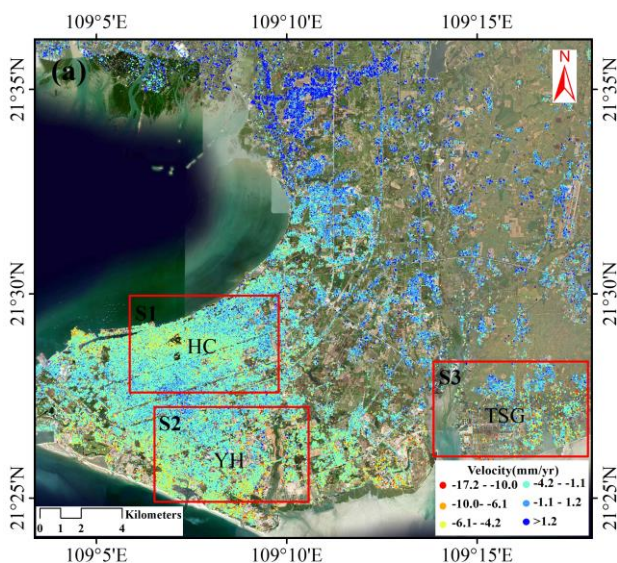

Figure 6. Feature area distribution map: (a) Three Subsidence Characteristic Areas in Beihai Area; and (b) a characteristic area of subsidence in Fangchenggang area A characteristic area of subsidence in Fangchenggang area.

Regions S1-S4 marked with red rectangles are major subsidence areas in Beibu Gulf. These areas will be further analyzed in the discussion section. HC, YH, TSG, and GK are the abbreviations of Haicheng, Yinhai, Tieshangang, and Gangkou, respectively.

Figure 7. Subsidence of characteristic area
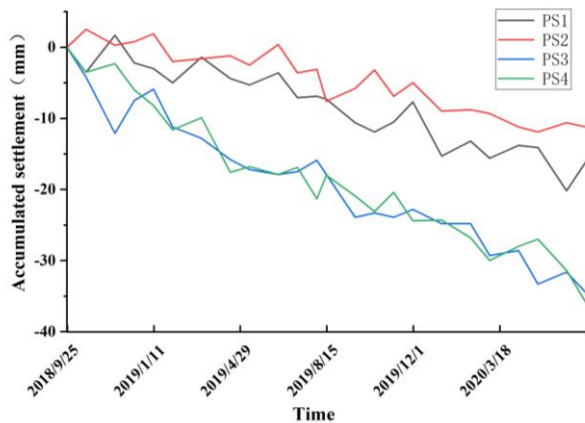The red triangle is the area where the timing points are located.

Figure 8. Time series accumulated subsidence in each region

4.3 Cause analysis

The two urban areas of Beihai are dominated by tourism development. In 2019, it has been approved as a "regional tourism demonstration area at the level of an autonomous region." In order to facilitate the development of tourism, human beings unreasonably exploit groundwater and infrastructure. For example, a series of Yintan transformation and upgrading projects were accelerated. The construction of several major cultural and tourism projects, such as Haisi first port and Gaode Binhai Cultural and tourism Complex, resulted in heavy loads in these two areas, resulting in large-scale surface subsidence. This leads to heavy loads in these two areas, resulting in large-scale surface subsidence. According to data, the main environmental disasters the North Sea faces are seawater intrusion, shoreline changes, and soil erosion. With the exploitation of groundwater, the cumulative amount of overexploitation from 2001 to 2010 reached 15 million cubic meters. However, in recent years, the government has banned and restricted the exploitation of some groundwater exploitation wells. It makes sound planning for surface water sources, resulting in a gradual decline in exploitation.

The main reason for the subsidence of the port area in the south of Fangchenggang is land reclamation. There is obvious subsidence in some areas. The port is built with foundation reinforcement, which is in a soft soil layer and has a large freight flow. In response to one belt, one road area, the area is to avoid uneven development between the people and the land, and to consolidate the land and expand the port areas. The data on soil and water loss in Fangchenggang City shows that Fangchenggang is due to natural factors (abundant rainfall, many mountains and steep slopes). The data on Fangchenggang City shows that natural factors (abundant rainfall, many mountains and steep slopes), production, construction, and indiscriminate mining have led to serious soil and water loss in Fangchenggang.

Due to the geographical location of Qinzhou, most of the areas are located inland, and only a small part of the areas are coastal areas (i.e., Qinzhou Bay). From the subsidence results of the study area, only Qinzhou Bay has a slight subsidence trend in the Qinzhou area. According to the information, shoreline change in the Qinzhou Bay was significantly complex in 2006–2008. during these two years, new lans emerge continuously. But after 2012, the coastline remained level. In other words, the reclamation area tends to be relatively stable (Yan et al., 2017).

In general, most of the locations where subsidence funnels occur are located in resource-rich coastal areas, also at the junction between plates, where silty soft soils are widely distributed and geological structures are prone to surface subsidence phenomena. In addition, frequent human activities, such as land reclamation and long-term excessive groundwater extraction, have disrupted the stress balance of geotechnical bodies, thus leading to the generation of ground subsidence.

5. CONCLUSION

In this paper, we adopted PSInSAR technique to monitor the subsidence in the Beibu Gulf region using 24 scenes Sentinel-1A images from 2018 to 2020, and analyzed the subsidence spatial-temporal evolution in the Beibu Gulf region to obtain the spatial distribution of major subsidence funnels and the subsidence time series pattern. Then, we selected the characteristic area to analyze the causes of land subsidence. The results show that:

(1) The subsidence rate of most subsidence areas in Beibu Gulf from -10.0mm/year to -1.1mm/year. And most of the subsidence areas are located in the coastal areas in the south of the study area (i.e., the Beihai and Fangchenggang areas). The subsidence areas in these places are obviously distributed, and the maximum subsidence rate can reach -17.2 mm/a. However, the subsidence areas of villages and towns located in Qinzhou in the north and inland of the study area are relatively stable.

(2) The subsidence areas are mainly concentrated in Yinhai District, Haicheng District and Tieshangang District of Beihai city. The annual average subsidence ranges from -10.0mm/year to -1.1mm/year. Among them, there is an obvious trend of subsidence in the Tieshan Port area, and the maximum accumulated subsidence is -34.5mm. Fangcheng District is the main subsidence area of Fangchenggang. The surface subsidence is widely distributed, showing a continuous subsidence trend, and the maximum cumulative subsidence can reach -35.9mm.

(3) The main influencing factors of land subsidence in the Beibu Gulf area are groundwater exploitation and solid mineral exploitation. Human factors such as tourism development, urban construction and industrial development also play an important role.

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