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# Monitoring and analysis of land subsidence in modern Yellow **River Delta using SBAS-InSAR Technology**

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Abstract. Modern Yellow River Delta has become one of the areas with serious land subsidence disaster in the plain area of Shandong Province. In this paper, Small Baseline Subsets -Interferometry Synthetic Aperture Radar (SBAS-InSAR) technology was used to process the Sentinel-1A data from August 2018 to October 2019 in the modern Yellow River Delta, in order to obtain the range and rate of land subsidence in the study area. At the same time, use the Leveling results of the same period to verify the accuracy. By selecting four larger land subsidence rate as feature points to analyze the characteristics of surface time series deformation, the influencing factors of land subsidence in this area are found out. The results show that during the past 2018-2019 years, the land subsidence in the the Yellow River Delta area was mainly distributed in Xianhe Town, southern the Huanghekou Town, Hubin Town, Guangrao County and its surrounding areas, DaWang Town, Yingli Town, Yangkou Town and the western part of Binhai Township, the most serious subsidence area is located in Xianhe Town, with an annual settlement rate of -204.7 mm/a. The land subsidence in the Yellow River Delta is mainly affected by groundwater overdraft, and the distribution characteristics of land subsidence funnel and deep groundwater depression funnel are basically consistent. In addition, natural factors such as consolidation of Quaternary loose sediments and regional tectonic movement also exacerbate the occurrence of land subsidence.

### **1. Introduction**

Land subsidence is a kind of environmental geological phenomenon, which is caused by the compression of the earth's surface soil under the action of natural and man-made factors<sup>[1]</sup>, and it will become a geological disaster in severe cases. Land subsidence disasters in China are mainly distributed in coastal Delta and coastal plain, and the land subsidence area accounts for about 80% of the total national subsidence area. Among them, the Yellow River delta region because of land subsidence caused by such as ground elevation loss, structural damage, storm surge disaster flooded, seawater intrusion, floods and increased pollution and so on a series of environmental geological problems<sup>[2]</sup>, the damage



to the development of society and economy is increasingly outstanding, has caused a large number of scholars concern<sup>[3-5]</sup>.

The traditional land subsidence monitoring methods mainly include GPS and leveling. These methods have high monitoring accuracy and can provide a good foundation for land subsidence research. In the Yellow River Delta area, many periods of measurement have been carried out. However, due to its low monitoring density and small coverage area, it is impossible to obtain the overall development characteristics of land subsidence, which brings great difficulties to the analysis of regional land subsidence. With the rapid development of space earth observation technology, InSAR (Interferometry Synthetic Aperture Radar) technology has been successfully applied to land subsidence observation due to its all-weather, large-scale, high-precision and high-density<sup>[6]</sup>. SBAS-InSAR (Small Baseline Subsets - Interferometry Synthetic Aperture Radar) technique is a new method of InSAR time series analysis proposed by Berardino<sup>[7]</sup>, Lanari<sup>[8]</sup> and others. It overcomes the limitations of time and space decorrelation and atmospheric effect in traditional D-InSAR (Differential Interferometric Synthetic Aperture Radar). Compared with PS-InSAR (Permanent Scatters Interferometric Synthetic Aperture Radar) method, SBAS-InSAR uses images with short time-space baseline to improve the coherence of interferogram, and the deformation sequence obtained is more continuous in time and space, so it can be applied to the slow deformation monitoring engineering of long time series. In recent years, many scholars in China have obtained surface deformation monitoring results using SBAS-InSAR technology, which is consistent with the actual situation and has a high accuracy <sup>[9-10]</sup>.

In this paper, SBAS-InSAR technology is used to study the land subsidence in the Yellow River Delta from August 2018 to October 2019, and the vertical cumulative settlement distribution and annual average settlement rate are obtained. Combined with leveling results, the accuracy and reliability of land subsidence in the study area obtained by SBAS technology are verified. On the premise of ensuring the accuracy of the results, this paper analyzes the spatial distribution characteristics and laws of land subsidence in the modern Yellow River Delta, and analyzes the causes of land subsidence in this area, so as to provide technical reference for further development of land subsidence prevention and control in this area.

#### 2. SBAS-InSAR Technology

The principle of SBAS-InSAR is: suppose time T0, T1, T2, ..., TN, there are N+1 radar images. According to the time and space baseline conditions, the combined small baseline subsets is L, and the differential interferogram formed by differential interferometry is M, M satisfies the following conditions:

$$\frac{N+1}{2} \le M \le \frac{N(N+1)}{2}$$
(1)

The interference phase of any pixel (x, y) in the i-th interferogram is:

$$\delta\varphi_i(x, y) = \varphi(t_B, x, y) - \varphi(t_A, x, y) \approx 4\pi [d(t_B, x, y) - d(t_A, x, y)]/\lambda$$
(2)

In formula (2),  $\lambda$  is the radar wave length,  $\varphi(t_A, x, y)$  and  $\varphi(t_B, x, y)$  represents the phase at time  $t_A$  and  $t_B$ ,  $d(t_A, x, y)$  and  $d(t_B, x, y)$  is the surface shape variable of the radar sight direction relative to the reference time  $t_0$ .

It is assumed that the main image time series arranged in time sequence is  $IE = [IE_1, \dots, IE_M]$ , auxiliary image time series is  $IS = [IS_1, \dots, IS_M]$ ,  $IE_i > IS_i$ . All the differential interference phases are:

$$\delta \phi_i = \phi(t_{IE_i}) - \phi(t_{IS_i}) \quad (i = 1, 2, \dots, M)$$
(3)

It is expressed by matrix:

$$\delta\phi_i = A\phi \tag{4}$$

Matrix A is a matrix with M rows and N columns. Each row of matrix A has two non-zero elements (1 and -1), which represent the interferogram, and each column represents the radar image of the corresponding period.

When  $M \ge N$ , N is the rank of coefficient matrix A, the least square method is used to solve the problem:

$$\varphi = \left(A^T A\right)^{-1} A^T \delta \varphi \tag{5}$$

When the rank of matrix A is less than N, the rank of coefficient matrix  $A^{T}A$  in formula (5) is deficient, which makes the solution of the equation innumerable. Therefore, in order to effectively solve this phenomenon, SVD method is used to solve the least square solution  $\phi$  in the sense of minimum norm theory.

The SVD method is used to solve the phase and the discontinuous deformation results are obtained. Based on this, it is transformed into the average rate of pixel points along LOS direction during adjacent image acquisition:

$$V_{t} = \left[ V_{1} = \frac{\varphi(t_{1})}{t_{1} - t_{0}}, \dots, V_{n} = \frac{\varphi(t_{N-1})}{t_{N} - t_{N-1}} \right]$$
(6)

By substituting formula (6) into formula (4), it is concluded that:

$$\delta \varphi_i = \sum_{i=IS_i+1}^{IE_i} \left( t_j - t_{j-1} \right) \cdot v_i \tag{7}$$

$$\delta \varphi = B_{v} \tag{8}$$

B is the M\*N matrix. For line i, the row B  $(i, j) = (t_j-t_{j-1})$  between the master and slave images, the other case is B (i, j) = 0. At this time, the singular value of B is solved to obtain the phase average rate of LOS direction in the sense of minimum norm, the DEM error is estimated combined with the settlement model, and then the settlement rate of each time period is integrated in time domain, get the shape variables of time series in Los direction. Finally, according to the incident angle, it is converted into the vertical deformation rate and the cumulative shape variable of the time series.

#### 3. Background and data processing

#### 3.1. Research background

The Yellow River Delta is located in Dongying City, Shandong Province, adjacent to Bohai Sea in the north and Laizhou Bay in the East. It includes Kenli County, Dongying City, Dongying District and surrounding villages and towns. It is the largest Delta in China. The terrain is generally gentle, which is high in the southwest and low in the northeast. The regional climate belongs to the warm temperate semi-humid and semi-arid continental monsoon climate, with four distinct seasons. The annual average temperature is 11.7-12.6 °C, and the annual average precipitation is 530-630 mm. The geographical coordinates of the study area are  $118 \circ 00$  ' E ~  $119 \circ 20$  ' E,  $37 \circ 00$  ' N ~  $38 \circ 40$  ' N, covering an area of 130 km × 120 km (Figure 1). The fault structure is especially developed in the area. According to the distribution direction of faults, it can be summarized as nearly EW direction, NE direction, NW direction and nearly NW direction. The fault activity is mainly tensional, and a small number of faults are also torsional. The Yellow River delta is a basin type sedimentary system. The Archean metamorphic rocks constitute the basement of the depression, which is covered by more than 10000 meters of sedimentary caprock. In the study area, the Cenozoic is well developed, including Paleogene, Neogene and Quaternary. The thickness of Paleogene is more than 7000 m, and the thickness of Neogene is 1000 -2000m. The Quaternary sediments are mainly alluvial proluvial and limnetic deposits of the Yellow River, with a sedimentary thickness of 370-450m <sup>[11]</sup>. This area belongs to the original loose rock hydrogeological area in North Shandong. The aquifer is mainly composed of fine sand and silty sand, while the aquitard is mainly composed of clay, sandy clay and silt. Taking the Shicun - YanXu -Daozhuang line in Guangrao County as the boundary, the groundwater in the northern marine alluvial

plain is mainly saline water, and the groundwater in the southern alluvial proluvial plain is the whole fresh water area, and the groundwater overdraft is serious, and there is a depression funnel.



Figure 1. The location of study area.

## 3.2. Data processing

Through SBAS-InSAR time series analysis, the land subsidence information of the modern Yellow River Delta from August 2018 to October 2019 is obtained. Figure 2 shows the land subsidence rate in the study area. The results show that in the monitoring period, the modern Yellow River Delta settlement distribution is uneven, and the land subsidence in some areas is serious, mainly distributed in Yingli Town, Xianhe Town, the south of Huanghekou Town, Hubin Town and Guangrao County The most serious settlement area is located in Xianhe Town, with the annual settlement rate of 204.7 mm/a from 2018 to 2019.



Figure 2. The map of subsided velocities (mm/a).

## 3.3. Accuracy verification

Leveling method is a conventional land subsidence monitoring method. Its operation time and cycle are long. It requires a lot of manpower and material resources, resulting in high cost and difficult to obtain continuous and large-scale deformation information. These reasons lead to its limited technological development. Because leveling can get high-precision elevation information of monitoring points, with its reliable technical advantages, it is usually used as the validation data of new land subsidence monitoring technology reliability. Therefore, in order to verify the accuracy and reliability of SBAS-InSAR technology monitoring results, the accuracy of SBAS monitoring results is evaluated according to the results of 17 two level leveling points obtained in the same area in the same period (Table 1). According to the evaluation and analysis, it is found that the mean square error of SBAS settlement monitoring results is 7.7 mm relative to the leveling results. The result shows a high degree of coincidence, and the accuracy of the mean square error can reach millimeter level, which meets the accuracy requirements. It proves that the monitoring results of SBAS-InSAR in the study area are timeliness.

fable 1.	Com	parison	table of	f leveling	g and	SBAS-	InSAR	monitoring	g results (	(unit: mm	).
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Point number	Level monitoring value	SBAS monitoring value	error
P1	-39	-39.3	-0.3
P2	-42	-44.6	-2.6
P3	-15	-26	-11
P4	-70	-78	-8
P5	-3	-7	-4
P6	0	-7.5	-7.5
P7	1	-4.4	-5.4
P8	2	-6.7	-8.7
Р9	-21	-25.6	-4.6
P10	-55	-54.2	0.8
P11	-72	-79.3	-7.3
P12	1	-7.9	-8.9
P13	3	-6.3	-9.3
P14	-46	-52.6	-6.6
P15	-63	-75.6	-12.6
P16	4	-4.9	-8.9
P17	-35	-41.8	-6.8
Mean square error		7.7	

### 4. Distribution of subsidence area

In Figure 3, the PS points are densely distributed in residential areas, roads, reservoirs, dams, and are clearly distributed along the roads and dams. The stability and reliability of the PS points are verified. Overall, there are four areas with higher sedimentation rate in the study area, i.e. A, B, C and D.

Area A is located near Zhanhua District, which is located in a typical shallow underground brine distribution area. A large amount of brine is exploited in the area, and the average value of land subsidence rate is 8.4 mm/a; area B is located in Xianhe Town, Gudao Town and surrounding areas. There are a large number of oil fields in the area, such as Gudao oilfield, Gudong oilfield, Zhuangxi oilfield, etc., with serious subsidence. Under the influence of oilfield exploitation activities, the average settlement rate is 18.1 mm/a, in which the maximum sedimentation rate is 204.7mm/a near Xianhe Town; area C is located in Huanghekou Town- the eastern part of Yong'an Town, the eastern part of the region is salt field area, with the average settlement rate of 9.6 mm/a and the maximum settlement rate of 160.3 mm/a; area D is mainly distributed in Guangrao-Dawang-Yingli-Yangkou Town, with the average settlement rate of 18.7mm/a. Due to the large range of settlement funnel, a relatively continuous settlement area has been formed. The maximum settlement rate of the settlement center in the north of Guangrao County is 109.8 mm/a, that of Dawang Town is 81.1 mm/a, and that of Yingli Town is 56.6 mm/a.



Figure 3. The subsidence rate diagram of each settlement area.

## 5. Influencing factors of land subsidence

According to previous research results, over exploitation of underground water, oil and gas and other underground fluid resources and solid mineral resources is the main cause of land subsidence, especially groundwater overexploitation<sup>[12-13]</sup>. Land subsidence caused by groundwater extraction is the result of interaction between stress field and seepage field. The effective stress of Terzaghi shows that the gravity of overlying soil and water is balanced by pore water pressure and effective pressure between particles. After pumping, the total pressure remains unchanged, the pore water pressure decreases and the effective pressure increases. The particle skeleton of soil is compressed due to the increase of stress, which shows the porosity decreases in the micro level, and the soil layer thins in the macro. Land subsidence in the Yellow River Delta is no exception. Since the late 1960s, Dongying City began to develop and utilize the deep groundwater. At first, the deep groundwater could still flow by itself, but with the increase of exploitation, the water level decreased year by year. In 1991, the water level was -10.01 m, in 2012 it was about-98 m, it has decreased by 88 m in the past 22 years, with an average annual decline rate of 4m/a. A regional funnel has been formed, which is based on the Dongying Shi Kou Chemical Plant, Shengli Power Plant, Guangrao County, Daozhuang, Caoqiao and DaWang Town. The funnel center is located in Guangrao County Economic Development Zone, Da Wang Town and Daozhuang Town. In 2019, the funnel area is 168.36 km<sup>2</sup> (70m equivalent buried depth coil), and the buried depth of central point water level is 107.39 m, which is 6.15 m lower than that in 2018. At present, the center of the ground subsidence funnel in the area is basically consistent with the area distribution of the groundwater drawdown funnel.

In addition, natural factors such as Quaternary unconsolidated sediments and basement tectonic activities have a certain impact on the occurrence of land subsidence. Nearly 60% of the area of the Yellow River Delta is soft soil layer, which is composed of nearly saturated or saturated cohesive soil,

silt and muddy silt<sup>[14]</sup>. It has the characteristics of high water content, low density, large pore ratio, high compression coefficient and low bearing capacity, which is easy to compress and lead to ground subsidence. According to the existing research results, the sediment settlement is mainly due to the consolidation settlement of soft soil layer, and it takes about 10 years to reach 90% consolidation degree<sup>[3]</sup>. At the same time, the Yellow River Delta is located in the area of long-term crustal subsidence since Paleogene. From 1951 to 1987, the land subsidence rate caused by tectonic movement in the Yellow River Delta was 5-10 mm/yr, among which the subsidence rate near Dongying City was 6.4 mm/yr<sup>[26]</sup>. The consolidation and neotectonic movement of Quaternary sediments in the the Yellow River delta plain have extensive and slow effects on the land subsidence. This change is generally not easy to be perceived. When it is superimposed with the ground subsidence caused by over exploitation of groundwater, it will cause harm to the social economy and the environment, so it can not be ignored either.

## 6. Conclusion

In this paper, SBAS-InSAR technology is used to process the Sentinel-1 radar images from August 2018 to October 2019, and the land subsidence information in the Yellow River Delta is extracted and analyzed from the aspects of subsidence area distribution, accuracy evaluation and influencing factors. The conclusion is as follows:

- From 2018 to 2019, the land subsidence in the Yellow River Delta is widely distributed, and the areas with serious subsidence mainly distribute in Xianhe Town, the south of Huanghekou Town, Hubin Town, Guangrao County and its surrounding areas, Dawang Town, Yingli Town, Yangkou Town and the west of Binhai Township. The most serious settlement area is Xianhe Town, with an annual settlement rate of 204.7 mm/a.
- Through the comparison analysis of SBAS-InSAR monitoring results and leveling results, the mean square error is 7.7 mm, which verifies the accuracy of SBAS-InSAR technology in large-scale land subsidence monitoring.
- The influence of groundwater overdraft in the Yellow River Delta area is more significant. The land subsidence funnel is consistent with the deep groundwater depression funnel. At the same time, natural factors such as Quaternary unconsolidated sediments and basement tectonic activities that cover the delta area also aggravate the occurrence of land subsidence.

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