SURFACE DEFORMATION MONITORING AND DRIVING FORCE ANALYSIS IN THE YELLOW RIVER DELTA BASED ON PS-INSAR TECHNOLOGY

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ABSTRACT:

Aiming at the land subsidence in the Yellow River Delta region, based on the Sentinel-1A data of 52 scenes from 2020 to February 2022, Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) were adopted to extract the surface deformation information of the Yellow River Delta region. Firstly, the deformation characteristics of typical subsidence feature points are analyzed, and then the correlation between groundwater, precipitation and land subsidence are analyzed. The result show that the settlement area distribution of the Yellow River Delta is not uniform, mainly distributed in underground brine mining area and oil extraction area, the maximum settlement center is located in Yongan Town, the settlement amount reaches -302.7mm, the main reason of the settlement is excessive exploitation of underground brine salt. By analyzing the correlation between groundwater, precipitation and land subsidence in the Yellow River Delta, it can be seen that the effect of groundwater content change on land subsidence was the most serious, and the correlation coefficient is 0.875. In general, the subsidence of the Yellow River Delta is mainly caused by the over-exploitation of underground fluids such as fresh water, brine and oil without timely compensation.

1. INTRODUCTION

Delta is a low-lying plain formed by a large amount of sediment carried by the river when it flows into the ocean, lake or other water bodies due to the decrease of flow velocity. Globally, the delta is one of the most densely populated areas in the world, with more than 500million people living in or near the coastal delta (Syvitski, et al., 2009). The coastal delta is the place where human survival and development and resources gather all over the world. It is the area with the most developed social economy, the most intense human activities, the most serious environmental impact, and the strongest demand for public security. It is also an area with fragile ecological environment (Zhang, et al., 2011). Due to the high compressibility of the soil in the delta region and a large number of human activities, land subsidence has become a serious geological disaster problem faced by many delta regions in the world (Chaussard, et al., 2013). Land subsidence makes the Yellow River Delta more vulnerable to coastal floods, wetland loss, coastline retreat and infrastructure loss, which directly affects the sustainable development of the local economy. Therefore, it is of great significance to monitor land subsidence in the Yellow River Delta in near real time, with high accuracy and wide coverage. In recent years, more and more detection technologies have been applied to the investigation and monitoring of land subsidence disasters. These technologies provide rich data sources In the early stage, leveling, global positioning system (GPS) and other methods were mainly used. With the development of radar observation technology, InSAR technology has become an effective means of space to earth observation with many advantages, such as large coverage, allweather, high resolution, high monitoring accuracy and periodic observation. In the monitoring of large areas, Synthetic Aperture Radar Interferometry (InSAR) technology is undoubtedly the most effective and appropriate technical means

to obtain the spatial-temporal distribution characteristics of surface deformation. (Andrea, et al., 2010.). The differential

synthetic aperture radar interferometry (D-InSAR) technology developed from InSAR technology has been widely used in land subsidence monitoring, and its theoretical accuracy can reach the accuracy of centimeter or even millimeter level (Andrew, et al., 1984). But this method can only calculate the deformation between two scene data, and with the passage of time, D-InSAR technology is vulnerable to spatiotemporal decoherence. In order to overcome the influence of these factors, researchers proposed PS-InSAR technology (Massonnet, et al., 1993), which only analyzes the time series of pixels that are stable for a long time and are not subject to temporal and spatial incoherence images, which can effectively separate the atmospheric delay phase and improve the accuracy of deformation monitoring (Ferretti, et al., 2001; Zhu, et al., 2020). At present, time series InSAR technology has been widely used in land subsidence monitoring in the delta region (Zhang, et al., 2009; Liu, et al., 2015).

Since 2000, experts and scholars have studied the causes of settlement in the Yellow River Delta. Many scholars believe that sea level rise, crustal tectonic movement and sediment consolidation and compaction are the main causes of land subsidence from a geological point of view (Li, et al., 2000; Shi, et al., 2007). With the deepening of research and exploration from different angles, the research on the cause and mechanism of land subsidence in the Yellow River Delta is also more targeted and specific. Experts and scholars have concluded through the analysis of oil field exploitation data, groundwater data, aquaculture data, etc (Liu, et al., 2013; Zhang, et al., 2014): compared with natural factors, human factors are the main cause of land subsidence in the Yellow River Delta.

To sum up, this paper uses sentinel-1a data from January 2020 to February 2022, uses PS-InSAR technology to monitor the recent surface deformation of the Yellow River Delta, and further analyzes the influencing factors of the land subsidence

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of the Yellow River Delta in combination with the changes of groundwater reserves and precipitation data.

2. POTENTIAL FOR LAND SUBSIDENCE IN YELLOW RIVER DELTA

2.1 Surface Geology of Western Yellow River Delta

The Yellow River Delta in Shandong Province extends around with the Yellow River Delta as the center. The modern Yellow River Delta is an alluvial fan formed with the swing and deposition of the estuary tail after the Yellow River was diverted from the Yellow Sea to the Bohai Sea in 1855. With Ninghai as the apex, it starts from the Taoer estuary in the north and ends at the mouth of Zimaigou in the south, covering an area of 5400 square kilometers. The terrain is flat and the altitude is mostly less than 6 meters. The modern Yellow River Delta consists of two parts: first, the Yellow River was already land before its diversion in 1855, and then delta sediments were accumulated on it because the distributary channel flowed through it; The second is the newly formed land that is constantly silted into the sea by the sediment carried by the Yellow River and reclaimed from the sea.

The Yellow River Delta is geologically located between the Chengning uplift area and the Jiyang depression area of the secondary structural unit of the North China platform, with different soil structures such as sand and clay and various types of saline soils with different salinization degrees. These micro landforms control the distribution of surface materials and energy, surface runoff and groundwater activities, forming a water and salt accumulation area centered on depressions. It is due to the gravity consolidation and compaction of the massive sediments brought by the Yellow River that the surface subsidence phenomenon appears in the Yellow River Delta area.

2.2 Human Activities

Salt ponds and aquaculture farms are widely distributed in the coastal areas of the Yellow River Delta Buildings are mainly distributed in Dongying City and small towns, and other areas are mostly farmland, wasteland or bare land. Shengli Oilfield, the second largest oil field in China, is located here, which is rich in oil, natural gas, brine and geothermal resources. Due to the abundant natural resources and the increasingly frequent human activities in the Yellow River Delta, there are more and more settlement funnels in the Yellow River Delta.

The shallow underground fresh water of well irrigation in the south of Xiaoqing River in Guangrao County is highly enriched. In the 1980s, two shallow groundwater depression funnels centered on Xigao village in Shicun town and Dongshui village in Daozhuang town appeared in the well irrigation area. The exploitation history of oil and gas resources in the Yellow River Delta region is long, and the pressure of the reservoir decreases greatly, which leads to the compression of the reservoir itself and the compression of the upper cohesive soil layer, and becomes the dominant factor of land subsidence in the oil and gas exploitation areas of the estuary area and Dongying area. In addition to exploiting underground fresh water and oil and gas resources, there are also large-scale underground brine mining areas in the Yellow River Delta. The distribution area of underground brine mainly includes Wudi-Zhanhua brine distribution area and Dongying brine distribution area. The long-term unreasonable exploitation of underground brine will cause the water level of underground brine to drop, and cause land subsidence. Underground brine is often used by chemical plants to produce bromine compounds and salts.

3. DATA COVERAGE AND METHOD

3.1 Data Coverage

The red line in Figure1. shows our data coverage. We use over C-band SAR images from descending tracks acquired by the Sentinel 1A satellite between January 2020 and February 2022, to cover Yellow River Delta. Sentinel-1A has the characteristics of multi polarization and high resolution, and the resolution can reach 5×20 m. The satellite has a variety of working modes, which can complete the radar imaging task all day and all weather. Sentinel-1a image has a width of 240km, and the revisit cycle is 12 d. The data used in this experiment are sentinel-1a images of 52 TOPS imaging mode provided by ESA. The polarization mode is VV polarization, and the incident angle is 33.733 °. The image coverage is shown in Figure 1.

3.2 Technical Principles of PS-InSAR

PS-InSAR technology selects one scene from the N+1 scene images as the main image, and the rest as the secondary image, and then use the main image to register, resample and interfere with the secondary image, and use the DEM data of the study area to remove the terrain phase, generate N differential interferograms, and obtain the differential phase of each pixel in each interferogram. Then the spectral coherence coefficient method and the amplitude dispersion threshold method are combined to select the highly coherent permanent scatterers. After, the nonlinear deformation phase and atmospheric phase are separated by filtering in time domain and space domain; Finally, the PS points will be selected for time series analysis, so as to obtain the shape variable and shape change rate. The PS-INSAR technology roadmap is shown in Figure 2.



Figure 1. The coverage area of Sentinei-1A



Figure 2. Data Processing Flow of PS-InSAR

4. DEFORMATION RESULTS AND ANALYSIS

In the process of data processing, the data on January 30, 2021 is selected as the main image to register other images, and the format of single view complex data is 10×2 , reducing the impact of noise and improving coherence. The terrain phase is simulated and removed by using SRTM DEM data with a spatial resolution of 30m. Since the Doppler centroid of Sentinel-1 terrain observation (TOPS) model data changes

greatly, highly strict co registration is required. Here, the external DEM is used for geometric alignment to realize the co registration of tops data. The deformation rate from January 2020 to February 2022 is shown in Figure 3.

The red mark in each figure indicates the master image for each dataset. The horizontal axis is the acquisition time for each image, and the vertical axis is the perpendicular baseline relative to the master image.





In order to analyze the deformation trend and influencing factors of each settlement area, this paper selects seven settlement areas, that is, the A-G mark in Figure 3, as the key areas for analysis. Select a feature point in each settlement area respectively. The cumulative shape variable changes of the seven feature points during 2020-2022 are shown in Figure 4.



Figure 4. Cumulative Deformation of each feature point

Combined with Figure 3 and Figure 4, it can be concluded that the maximum cumulative settlement of the seven settlement areas is 302.7mm, and the maximum settlement rate of area D is 139.71mm/a. The spatial distribution of the seven subsidence areas is close to the oil and gas exploitation area and the underground light brine exploitation area. It is preliminarily considered that the subsidence is caused by the overexploitation of underground resources without timely compensation. It is worth noting that the settlement trend in various regions gradually slowed down from January 2021 to September 2021. The causes of the seven subsidence areas are analyzed one by one in combination with the geographical location of each subsidence area and the distribution of underground resources.

Zone A is located in Binhai town and Fengjia town of Zhanhua District, which is a typical shallow underground brine distribution area. The cumulative deformation of zone a is -187.51mm. The main reasons for the settlement in this area are the overexploitation of underground brine for bromine and salt drying.

Zone B is located in Guanghe village guoxingxing salt farm on the west side of the old Yellow River in Hekou District[3], the maximum cumulative deformation is -128.79mm, and this area has an upward trend since September 2021. Zone C is located in the East and northwest of Xianhe Town, Hekou District, with the maximum cumulative deformation of -125.86mm. Salt farms and salt fields in these areas mainly dry salt by extracting a large amount of underground brine. B and C are not only affected by a large number of underground brine mining, but also related to the geological conditions of the area. Soft soil with high water content and high compressibility is widely distributed in areas B and C (Wang and Qin, 2020), resulting in land subsidence in the estuary area before the 1980s when the exploitation of underground brine resources was still low (Wang and Ji, 2020).

D and E two subsidence areas belong to Dongying brine distribution area, and the maximum cumulative deformation variables are -302.72mm and -282.95mm respectively. Area E is located in the northeast of Shengli airport. The formation lithology of this area is mainly silt, and the underground brine has been extracted and baked into salt since the 20th century. Geological structure and human activities are the main reasons for the land subsidence in this area (Zhang, et al., 2020). Zone E is located in Yangkou Town, which is a national fishing and salt featured town. The core of its salt production is Yangkou salt field. Due to the development of brine industry, there is a great possibility of overexploitation of underground brine in this area, resulting in obvious land subsidence in this area.

Zone F is located in Shicun Town, Guangrao town and Huaguan town south of Xiaoqing River in Guangrao County. The maximum cumulative deformation variable in this area is -178.86mm. The concentration of underground fresh water in this area is high, including both shallow groundwater exploitation areas and deep groundwater exploitation areas. At present, it has reached overexploitation, so the main reason for land subsidence in this area is the long-term exploitation of underground fresh water resources.

Zone G is located in Jinjia oil field in Maqiao Town, Huantai County, with the maximum cumulative deformation of -64.155mm. The main reason for the land subsidence in the oil production area is that the pressure of the oil reservoir decreases and the supporting force of the topsoil decreases due to the long-term large-scale exploitation of oil, so the surface soil compression causes the land subsidence

5. ANALYSIS OF INFLUENCING FACTORS OF LAND SUBSIDENCE

5.1 Relationship between Land Subsidence and Groundwater

According to the analysis in the third section, six settlement funnels in the Yellow River Delta during the monitoring time are located in the groundwater resources exploitation area, and one is located in the oil exploitation area. The mined underground brine is not only directly used for salt drying and bromine production, but also used for oil well water injection (Zhang, 2015). Therefore, the exploitation of groundwater resources may have a greater impact on land subsidence in the Yellow River Delta. In order to verify the relationship between surface deformation and groundwater data in the Yellow River Delta, this paper makes a correlation analysis between cumulative deformation variables and groundwater data in the Yellow River Delta. Considering the difficulty of obtaining groundwater data, this paper combines GRACE-FO satellite data and GLDAS data to retrieve the changes of groundwater reserves in the Yellow River Delta from January 2020 to February 2022.

The main task of the GRACE-FO satellite is to accurately measure the temporal and spatial changes of the earth's gravity field. The anomalies of land water reserves monitored by GRACE-FO mainly include the anomalies of ice and snow, surface water, soil water and groundwater. In this paper, the Rl06 data provided by Jet Propulsion Laboratory (JPL) is $0.5^{\circ} \times 0.5^{\circ}$ spatial resolution and with a time resolution of 1 month. Equation (1) is the change expression of land water reserves retrieved from GRACE-FO satellite data:

$$\Delta_{\rm TWS} = \Delta_{\rm CAN} + \Delta_{\rm SWE} + \Delta_{\rm SM} + \Delta_{\rm Ground} \tag{1}$$

In the formula, $\Delta_{TWS} \propto \Delta_{CAN} \propto \Delta_{SWE} \propto \Delta_{SM} \propto \Delta_{Ground}$ represent the changes of land water reserves, canopy water content, snow water equivalent, soil water and groundwater retrieved by GRACE-FO satellite respectively.

In order to get the change of groundwater, it needs to be further processed in combination with GLDAS data. GLDAS is jointly developed by NASA's Gotha Aerospace Center (Goddard Space Flight Center , NASA) and the National Center of environmental prediction (NCEP). The model obtains the changes of surface fluid through real-time acquisition of satellite remote sensing observation data and surface observation data, and through advanced surface model and data assimilation technology. This paper adopts GLDAS data based on Noah land surface hydrological model (Hereinafter referred to as GLDAS_Noah), its spatial resolution is $0.25^{\circ} \times 0.25^{\circ}$, with a time resolution of 1 month. The data has been processed by relevant smoothing and so on. Equation (2) is the change of water resources calculated by GLDAS_Noah data.

$$\Delta_{\rm GLDAS} = \Delta_{\rm CAN} + \Delta_{\rm SWE} + \Delta_{\rm SM} \tag{2}$$

In the formula, Δ_{GLDAS} , Δ_{CAN} , Δ_{SWE} , Δ_{SM} respectively represent the total amount of water resource changes, canopy water content changes, snow water equivalent changes, and soil water changes (including soil water changes of 0-10cm, 10-40cm, 40-100cm, and 100-200cm) calculated by GLDAS_Noah. According to formula (1) and formula (2), the change of land water reserves obtained from the total amount of the change of land water reserves obtained from the inversion of GRACE-FO data minus the change of water resources extracted by GLDAS_Noah. Figure 5 shows the comparison of GRACE-FO data and GLDAS_Noah data in the Yellow River Delta from January 2020 to February 2022. Figure 6 shows the changes of groundwater reserves in the Yellow River Delta region after smoothing in some months from January 2020 to February 2022.



Figure 5. GRACE-FO Data Compared with GLDAS_Noah Data

It can be seen from Figure 5 that the water resource change retrieved from GLDAS_Noah data is in good agreement with the land water reserve change retrieved from GRACE-FO data. The peak and peak valley appear at roughly the same time. The reason for the difference is that the GLDAS_Noah data used in this paper only includes the changes of land soil water, surface water and ice and snow water, while the changes of land water reserves retrieved from GRACE-FO data also include the dynamic changes of groundwater.

In order to further verify the relationship between surface variables and groundwater changes in the Yellow River Delta, this paper calculates the mean value of the time series deformation results of all monitoring points, and represents the groundwater changes in the Yellow River Delta with the mean value of grid data at different positions in the groundwater data. A total of 26 groups of cumulative shape variables and groundwater changes are obtained. This paper makes a regression analysis between the average time series cumulative shape variable and groundwater change in the Yellow River Delta, and the specific results are shown in Figure 7.



Figure 6. Cumulative changes in groundwater time series from 2020 to 2022



Figure 7. Correlation between cumulative shape variables and changes in groundwater reserves

It can be seen from Figure 7 that the cumulative shape variable of the average time series is positively correlated with the change of groundwater, and the correlation coefficient R value is 0.875. According to the critical value table of correlation test, when the degree of freedom is 26 and the significance level is 0.05, the threshold of correlation coefficient is 0.268. From the above analysis, it can be seen that there is a strong correlation between the average time series cumulative shape variable of the Yellow River Delta from January 2020 to February 2022 and the change of groundwater, which further verifies the impact of groundwater change on the land subsidence of the Yellow River Delta.

5.2 Relationship between Land Subsidence and Precipitation

The time of brine mining in the Yellow River Delta has a certain relationship with the climate. Generally speaking, in the middle and late April of spring, the temperature in the Yellow River Delta region is higher than that in winter, and the rainfall is less. At this time, it is more suitable to extract underground brine for salt drying. The brine wells are gradually opened from "peak valley level" to all day (Yao and Yuan, 2013). In late June in summer, the Yellow River Delta begins to enter the rainy season, the precipitation will gradually increase, the salt drying work is not easy to carry out, and the brine well will gradually shorten the pump on time. At this time, the underground brine exploitation will gradually reduce.

In order to verify the relationship between the settlement of the Yellow River Delta and precipitation, this paper uses the monthly average precipitation and the deformation results of the Yellow River Delta for regression analysis. In order to ensure the uniformity of data, the accumulated deformation of the existing average time series is processed by difference, and the monthly average interval shape variable is obtained by subtracting the previous time phase from the latter time phase. The linear fitting equation obtained from the regression analysis of monthly average interval variables and monthly average precipitation is shown in Figure 8.



Figure 8. The relationship between interval variables and precipitation data

It can be seen from Figure 9 that the average interval shape variable of the Yellow River Delta is positively correlated with the monthly precipitation, and the correlation coefficients is 0.461. Comprehensive analysis shows that the average interval shape variable of the Yellow River Delta is moderately correlated with the monthly precipitation. Compared with groundwater, the influence of precipitation on surface deformation in the Yellow River Delta is weak.

6. ANALYSIS OF INFLUENCING FACTORS OF LAND SUBSIDENCE

In this paper, the PS-InSAR technology is used to process 52 Sentinel-1A data in the Yellow River Delta, and the surface deformation results from January 2020 to February 2022 are obtained. We found that the Yellow River Delta is still facing serious land subsidence. Settlement funnels are mainly distributed in oil and gas production areas and underground brine production areas. The main reason for the subsidence of the Yellow River Delta is the overexploitation of underground resources without compensation. We also analyze the correlation between the results of surface deformation and groundwater changes and precipitation. Specifically, the major findings obtained through this research are as follows: First, the settlement area of the Yellow River Delta is extremely uneven, and the maximum settlement point is located in Yong'an Town, with a cumulative deformation of -302.7mm. The distribution position of settlement area is basically consistent with the monitoring results of previous literature.

Second, the variation trend of deformation variables in 7 significant subsidence areas in the Yellow River Delta is analyzed. From January 2021 to September 2021, the settlement of each characteristic point gradually slows down, and the settlement of areas A, B, E and G accelerates again since September 2021.

Finally, by analyzing the correlation between the change of groundwater reserves, precipitation and the regional surface deformation of the Yellow River Delta, it is concluded that the overall surface deformation of the Yellow River Delta has a strong correlation with the change of groundwater reserves, and the correlation coefficient reaches 0.875. However, the interval variables in the Yellow River Delta are moderately correlated with the local monthly average precipitation, and the correlation coefficients is 0.461.

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