Monitoring and predicting land subsidence associated with land creation over Yan'an New City (China) by using time series InSAR technique

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Abstract. New flat land was created in Yan’an (China) through bulldozing mountains and filling valleys for subsequent urban construction. This creation may cause severe environmental problems, with major concern on the large-scale land subsidence. However, large-scale high-precision monitoring and predicting works haven’t been conducted in this region. Based on this background, time series Syntenic Aperture Radar Interferometry (InSAR) technique is adopted in this region to process 165 C-band Sentinel-1A data with purpose of mapping land subsidence associated with land creation. The result shows that clear subsidence is observed in the filling area, where the maximum subsidence reaches 6 cm/y. Meanwhile, phenomenon of alternate uplift and subsidence reflects the complexity of deformation due to the land creation. When connecting subsidence with the filling thickness, building distribution and local precipitation, it is found that the magnitude of subsidence in YANC is controlled by filling thickness and precipitation. The Asaoka model was used to predict the land subsidence and indicated that the subsidence will be stable in the future five years. Our observation may have significant implications for effective land creation, urbanization planning and land subsidence management decision, where mountains are bulldozed to increase the space available for urban development.

1. Introduction
The limited supply of available land is an important impediment for rapid urbanization in China. To solve this problem, the Chinese government launched a campaign of creating new land through bulldozing mountains and filling valleys in some upland cities [1]. This land creation project has contributed greatly to urban construction and the local economy. However, the evidence has showed that it may cause severe environmental problems, with major concern on the large-scale land subsidence [2]. This subsidence brings a major threat to urban construction and local human life [3].

As a typical land creation region, Yan’an New City (YANC), China was established in April 2012 and had experienced rapid urbanization [4]. However, until now, large-scale high-precision monitoring and predicting works have not been conducted in this region. Based on this background, the time series Syntenic Aperture Radar Interferometry (InSAR) technique is adopted in this study to investigate the temporal and spatial evolution of deformation in YANC.

2. Study area and data processing
The study area is located at the northwest of China and surrounded by mountains. To expand the available space for subsequent urban construction, local government launched a campaign in 2012 to
remove the upper section of mountains to fill in valley areas, as shown in Figure.1. After removing and filling, new flat land with an area of 24 km$^2$ was created (Figure.1(a)). Figure.1(b) shows the topographic variations from 2001 to 2015, where clear filling and digging areas are identified. The statistics indicates that maximum filling and digging depth is above 110 m. Figure.1(c) shows the surface changes from 2014 to 2019 and we can see that intensive constructions have been implemented over YANC.

Figure. 1 The land creation project over Yan’An New City (a) diagram of bulldozing mountains and filling valleys project; (b) DEM changes between 2001 and 2015; (c) surface changes between 2014 and 2019.

A total of 165 C-band Sentinel-1A data are collected for this study (Table.1), which allows us to obtain the ground deformation over YANC from October 23, 2014 to December 2, 2020. Meanwhile, TanDEM-X global DEM product with resolution of 1 arc-seconds (30m) is used as an external DEM to remove the topographic phase from the differential interferograms.

Table.1 Sentinel-1 data employed for processing

| Sensor | First Image | Last Image | Orbit Pass | Number of Acquisitions |
|--------|-------------|------------|------------|------------------------|
| S1-A   | 23/10/2014  | 02/12/2020 | Ascending  | 165                    |

Using the collected SAR and DEM data, Small Baseline Subset DInSAR (SBAS-DInSAR) technique, which is based on an appropriate combination of differential interferograms produced by data pairs, is applied to derive the time series deformation [5]. The main processing steps include: (1) generating 322 interferograms by setting spatial baselines of < 150 m and temporal baselines of < 250 days; (2) removing the topographic phase and reference phase, filtering the interferograms and retrieving the original (unwrapped) phase signals from wrapped phase; (3) inverting of the unwrapped interferograms for the retrieval of the time series of deformation; (4) detecting and subsequently removing possible atmospheric artifacts. The iterative processing is conducted to map the final time series deformation over YANC region.

3. Results and analysis

3.1. Spatio-temporal evolution of land subsidence

Deformation rate is generated to illustrate the spatial distribution of land subsidence over YANC (Figure.2(a)). It can be seen that high subsiding rate is distributed over study area, where the maximum subsidence reaches to 6 cm/y. A detailed analysis is conducted over the areas with large subsidence. Firstly, it is found that the distribution of subsidence is consistent with the distribution of filling areas when connecting Figure.1(b). For the excavation area, it is nearly no subsidence happened in this region.
This observation indicates that the subsidence in YANC is mainly due to the loose soil compaction. Secondly, magnitudes of subsiding rate are different among different regions. It is difficult to explain this phenomenon, but we think it may be related with the filling time, filling thickness, filling materials, stress of high buildings [6]. To sum up, the spatial distribution of surface subsidence in YANC is controlled by the filling area. Figure 2(b) shows the time series deformation at point P marked in Figure 2(a). It can be found that the deformation presents an approximate linear variation with time, where the cumulated subsidence is about 55 cm from October 23, 2014 to December 2, 2020. However, conspicuous alternate uplift and subsidence are also observed. It should be noted that there is a sharp subsiding from September to October and February to March. This variation is likely related with the precipitation according to previous investigation.

Figure 2 InSAR-derived land subsidence over Yan’An New City (a) deformation rate; (b) time series deformation from October 23, 2014 to December 2, 2020.

3.2. The causes of land subsidence
In order to analyze the causes of land subsidence in YANC, the correlation is investigated among subsidence, topographic variations, construction distribution and precipitation. Figure 3(a) shows the correlation between land subsidence and DEM variations. It is clear that the magnitude of subsidence in YANC is controlled by filling thickness, where the thicker filling soil means the larger subsidence. The study area was filled by a large area of loess, which had many unfavorable properties regarding their use in project such as high compressibility. In this context, the subsidence was easily occurred due the natural consolidation of the soils. Therefore, the thicker filling soil was more easily compressed with result of severe subsidence. Figure 3(b), displaying the building distribution in YANC, indicates that there is the weak correlation between land subsidence and stress of buildings. Meanwhile, the evidence shows that the land subsidence in YANC is also correlated with the local precipitation, which may lead to the periodic deformation, as shown in Figure 3(c).
3.3. Prediction of subsidence

Asaoka model, a simple deformation prediction model based on one-dimensional vertical consolidation theory, is adopted to predict the subsidence in YANC [7]. Figure 4 shows the result of land subsidence prediction at point P. It is well consistent with the InSAR-derived deformation from October 23, 2014 to December 2, 2020, where the prediction precision is about 4.5 mm. In the future five years, the subsidence will be stable.
4. Conclusions
A total of 165 C-band Sentinel-1A data is processed to map the land subsidence associated with land creation over YANC. The result shows that clear subsidence is observed in the filling area, where the maximum subsidence reaches to 6 cm/y, indicating the correlation between subsidence and loose soil compaction. Meanwhile, phenomenon of alternate uplift and subsidence in YANC reflects the complexity of deformation due to the land creation. The result shows that clear subsidence is observed in the filling area, where the maximum subsidence reaches to 6 cm/y. Meanwhile, phenomenon of alternate uplift and subsidence reflects the complexity of deformation due to the land creation. When connecting subsidence with the filling thickness, building distribution and local precipitation, it is found that the magnitude of subsidence in YANC is controlled by filling thickness and precipitation. The Asaoka model was used to predict the land subsidence and indicated that the subsidence will be stable in the future five years. Our observation may have significant implications for effective land creation, urbanization planning and land subsidence management decision, where mountains are bulldozed to increase the space available for urban development. Our observation may have significant implications for effective land creation, urbanization planning and land subsidence management decision in YANC, where mountains are bulldozed to increase the space available for urban development.

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