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Open-Cast Mining Deformations Monitoring using Sentinel-1 SAR data (SBAS technique)

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Abstract

Land surface deformation created by mining activities can have negative impacts on the environment. Measuring them can be a tool for managing the environmental impacts of mining. Synthetic Aperture Radar Interferometry is a remote sensing method for measuring deformations. The main aim of this research is to investigate the deformation phenomenon on a region scale and extend our understanding of it to all mining deformation areas across the country. This paper used Small Baseline Subset Interferometric Synthetic Aperture Radar technology to obtain deformations information in the Sangan mine based on mining activities. We used 48 scenes of Single Look Complex(SLC) data acquired by the Sentinel-1A, C-band of the European Space Agency descending orbit paths from 2014 to 2020. The Time Series of SBAS results show that the deformation velocity rate is about –20 to –35 mm/yr, and the displacement is attributed to approximately –120 mm in the Line of Sight direction. The main deformation zone is situated in the mining area on the main alluvial fan. This study presented the relationship between deformations and mining activity's effects on the ground. Mining activities were accompanied by ground deformation in the mining area: the ground deformation is exacerbated by the increasing mining quantity, and as a result will cause erosion, flood, and other geomorphologic phenomena in the area. We compared the results of the SBAS technique with leveling data for validating the data of SBAS. Their comparison shows approximately suitable agreement with the results of SBAS.

Keywords

SBAS Technique, Sangan mines, deformation, SAR data.

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Open-cast mining deformations monitoring using Sentinel-1 SAR data

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Abstract

Land surface deformation created by mining activities can have negative impacts on the environment. Measuring them can be a tool for managing the environmental impacts of mining. Synthetic Aperture Radar Interferometry is a remote sensing method for measuring deformations. The main aim of this research is to investigate the deformation phenomenon on a region scale and extend our understanding of it to all mining deformation areas across the country. This paper used Small Baseline Subset Interferometric Synthetic Aperture Radar technology to obtain deformations information in the Sangan mine based on mining activities. We used 48 scenes of Single Look Complex (SLC) data acquired by the Sentinel-1A, C-band of the European Space Agency descending orbit paths from 2014 to 2020. The Time Series of SBAS results show that the deformation velocity rate is about −20 to −35 mm/yr, and the displacement is attributed to approximately −120 mm in the Line of Sight direction. The main deformation zone is situated in the mining area on the main alluvial fan. This study presented the relationship between deformations and mining activity's effects on the ground. Mining activities were accompanied by ground deformation in the mining area: the ground deformation is exacerbated by the increasing mining quantity, and as a result will cause erosion, flood, and other geomorphologic phenomena in the area. We compared the results of the SBAS technique with leveling data for validating the data of SBAS. Their comparison shows approximately suitable agreement with the results of SBAS.

Keywords: SBAS technique, Sangan mines, deformation, SAR data

1. Introduction

Surface deformations in mines are one of the most critical issues in the global ecosystem processes [1]. Open-cast mines cause topographic deformations on the Earth [2,3]. Deformations by mining activities can cause drastic geomorphic changes in the mine's landscape, affecting the surface evolution of the Earth and decreasing the original site drainage network, and causing the intensification of some of the geomorphic processes and forms like erosion, flood, landslide. The surface deformation caused usually presents a non-linear characteristic due to the nature of mining activities, which bring out relatively rapid surface deformation. Therefore, using advanced technology to monitor and control damage caused by ground surface deformation is necessary. Detection of surface deformation can be obtained from different techniques: traditional surveying techniques using leveling techniques, theodolites, TS, and GPS, or geotechnical methods, such as extensometers, inclinometers, piezometers and crack measuring pins are the main deformation monitoring systems used over mining [4]. The advantages of these techniques are their direct observations and high accuracy. However, they are difficult to mount in dangerous areas and cannot cover the whole target of interest. They also are time-consuming when the region becomes large [5] and are done one time per year, and are usually to a few square kilometers [6]. In recent years satellites based on remote sensing

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technologies have been utilized for deformation monitoring. "Space geodetic techniques are particularly useful for determining the extent and current state of ground displacement over mining areas, with many benefits arising from the use of synthetic aperture radar (SAR) data" [7,8]. Synthetic Aperture Radar Interferometry (InSAR), as one of the effective techniques for land surface deformation monitoring, has been used in the investigation. "It derives information by using the interferograms which are formed by phase differences between two complex SAR images of the same area but obtained at slightly different positions with the same sensor" [9] and is a powerful method for deformations measurement spatially on large areas [10]. That is an active sensor, widely used to measure the topographic, subsidences, and surface deformations [11,12] and does not rely on the natural illumination of the sun, and with a longer wavelength compared to optical images, the signal passes through clouds providing a clear view of the area of interest. The InSAR idea was suggested in the last 1980s [13]. Multiple satellites are circling the terrain, achieving radar images of the land's surface, usually monitoring and mapping the land's surface. Radar images are produced in several bands, such as X, C, and L bands. In this paper, Sentinel-1A (S1-A) has used C-band SAR images. The Sentinel-1 Interferometric wide swath (IW) covers a larger area with a high spatial resolution, and the products strip width is around 250 km. The Sentinel-1 products are able to detect minor land deformations in different climatic areas [14]. In particular, the re-imaging time of the Sentinel-1 IW data sensor is for a short point, the bandwidth is very high, and it can take pictures of larger areas [15,16]. The Interferometric Wide swath (IW) mode implements a new type of ScanSAR mode called Terrain Observation with Progressive Scan (TOPS) SAR aimed at reducing the drawbacks of the ScanSAR mode. The basic principle of TOPSAR is the shrinking of the azimuth antenna pattern (along-track direction) as seen by a spot target on the ground. This is obtained by steering the antenna in the opposite direction as for Spotlight support. TOPS employs a rotation of the antenna in the azimuth direction. Similar to ScanSAR, several sub-swaths are acquired quasi-simultaneously by

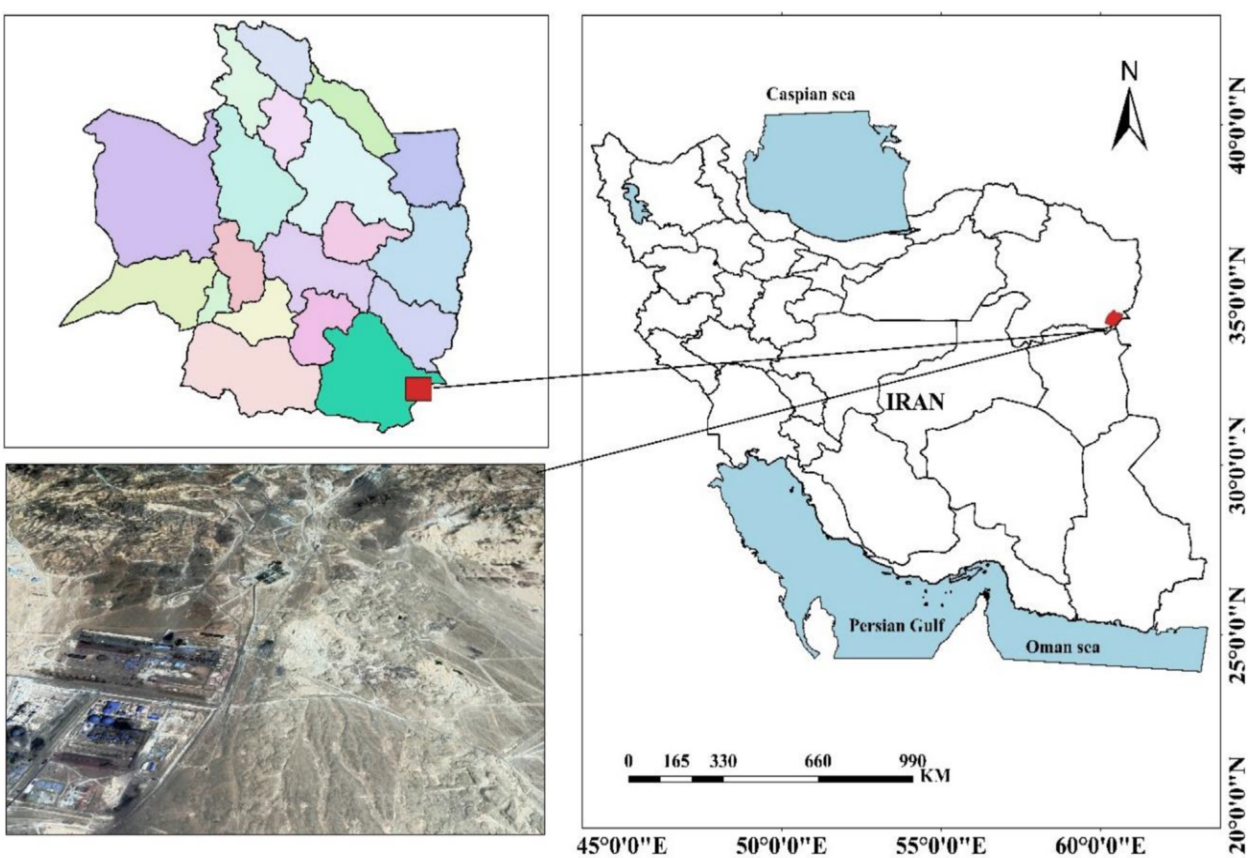

Fig. 1. Location map of the study area. The districts are highlighted by colors.

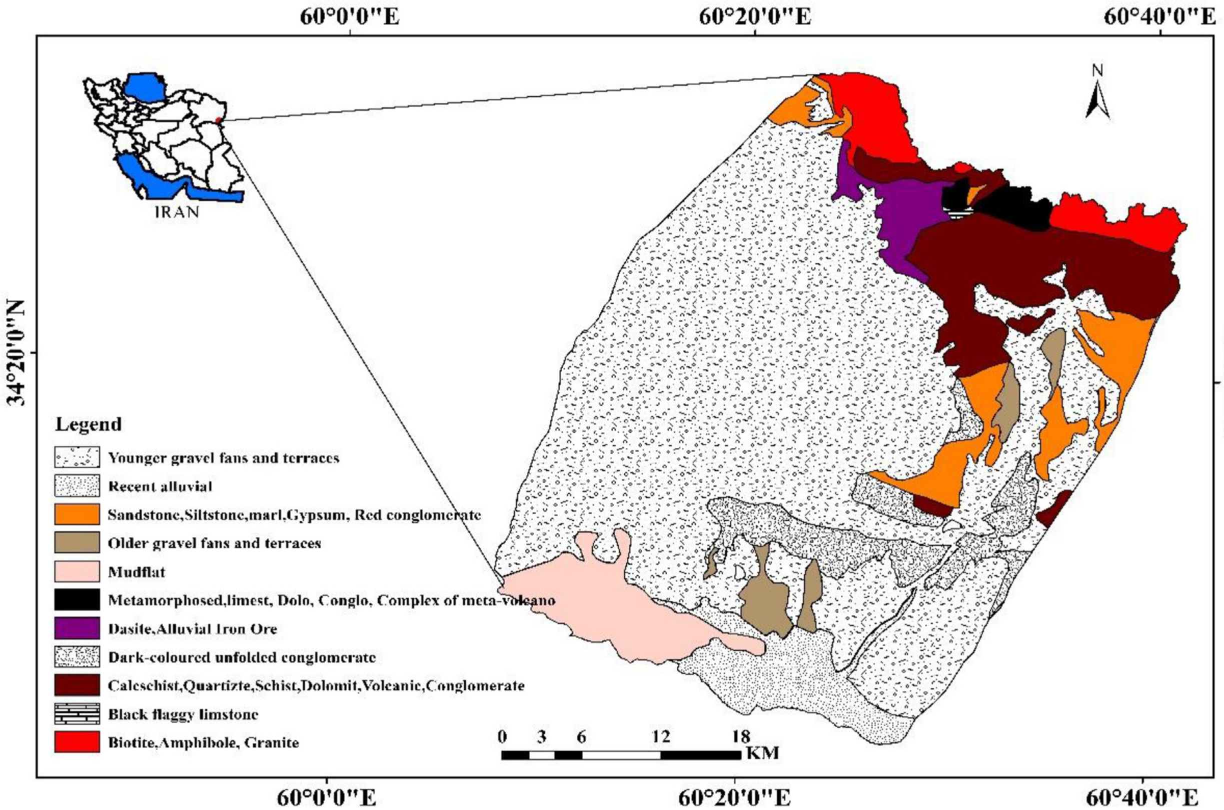

Fig. 2. Geology map of Sangan Mines.

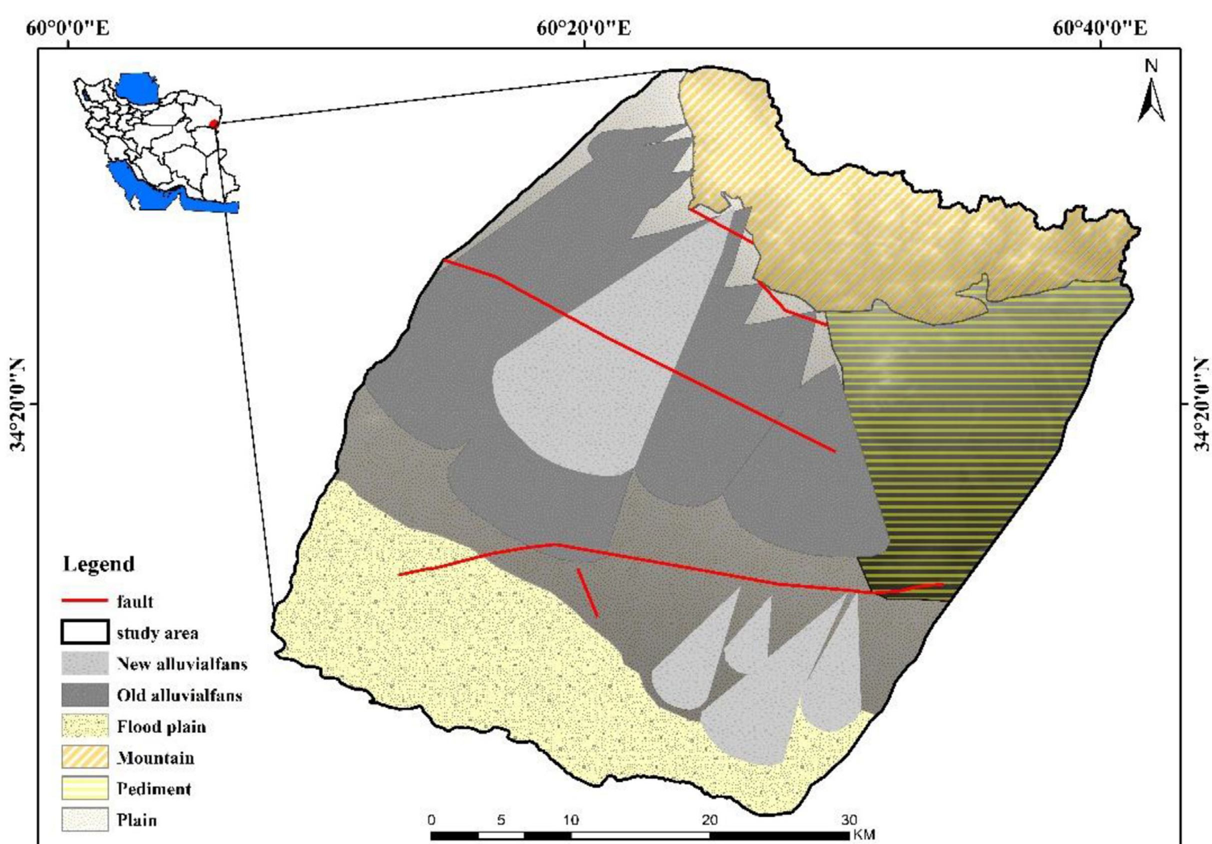

Fig. 3. Geomorphology units' map of Sangan Mines.

sub-swath switching from burst to burst. The increased swath coverage is achieved by a reduced azimuth resolution, as in ScanSAR. However, in TOPS, the resolution reduction is obtained by shrinking virtually the effective antenna footprint to an on-ground target rather than slicing the antenna pattern, as happens for ScanSAR. The Sentinel-1 C-SAR system is designed to enable TOPS burst synchronization of repeat-pass data-takes supporting the generation of TOPS interferograms and coherence maps. Specifically, for the IW and EW modes, the TOPS burst duration is 0.82 s and 0.54 s (worst case), respectively, with a requirement for achieving synchronization of less than 5 ms between corresponding bursts. TOPSAR requires high accuracy for image co-registration. A small co-registration error in azimuth can introduce an azimuth phase ramp due to the SAR antenna azimuth beam sweeping causing Doppler centroid frequency variations of 5.5 kHz. In radar images, the amplitude and phase of the return signals are recorded. To map the topographic deformations between two acquisitions in a SAR image pair, the same area's repeated images are used. This couple is achieved by the same sensor and satellite. The future acquisition must be planned so that future images also be acquired from the same orbital position or minimum deviation. This deviation orbital location of the platform is called the baseline position [17]. This method over the period of accessible data, helps to estimate the smallest deformation rate in the surface. To map the deformations rate and time series calculation, repeated images of an area are used. It means that monitoring the deformation by measuring the phase difference uses a minimum of two SAR data achieved at different times of the identical area on the ground. Atmospheric errors and orbital errors can reduce the accuracy of InSAR. It means that traditional InSAR technology is significantly affected by spatial and temporal coherence and the effects of atmospheric delay. Therefore, MT-InSAR (Multi-temporal InSAR) strategies have been used to reduce atmospheric and orbital errors [18]. These techniques are used to extract time series and deformation rates by means of a network of several acquisitions. In MT-InSAR methods generally are used PS (permanent scatter) [19] and Small Baseline Subset (SBAS InSAR) [20]. In this paper, the Sangan mine has been chosen for Time-Series analyses by Small BAseline subset (SBAS) technology. Berardino et al. [21] introduced SBAS as a Multi-Temporal InSAR methodology. The ability of SBAS to detect has been approved in different applications, mainly on SAR data. SBAS technology can process SAR images to obtain accurate surface deformation information. SBAS works with distributed targets, and it produces many interferograms of the SAR data in the same region at different dates by setting spatial and temporal baselines. Then it does analyses on all the interferograms to acquire the deformation results of time series (TS) [7,21,22]. The core idea of

Table 1. Imaging parameters of SAR image.

Date of acquisition	Temporal baseline (day)	Special baseline (m)
2,017,287	**0**	**0**
2,014,279	279	25.99
2,014,351	351	35.72
2,015,010	375	48.15
2,015,070	435	−84.40
2,015,142	507	−9.01
2,015,166	531	87.29
2,015,190	555	−113.15
2,015,238	603	38.85
2,015,274	639	−13.33
2,015,322	687	−11.93
2,015,346	711	124.68
2,016,005	735	14.49
2,016,077	807	−23.97
2,016,149	879	−19.89
2,016,197	927	−15.63
2,016,245	975	−20.69
2,016,293	1023	−21.80
2,016,317	1047	37.79
2,016,365	1095	124.63
2,017,023	1118	13.51
2,017,071	1166	58.93
2,017,131	1226	68.14
2,017,191	1286	7.22
2,017,251	1346	29.95
2,017,323	1418	63.39
2,018,006	1466	11.86
2,018,054	1514	−54.82
2,018,078	1538	−28.34
2,018,138	1598	−14.53
2,018,174	1634	10.83
2,018,210	1670	−40.73
2,018,270	1730	15.72
2,018,330	1790	18.02
2,018,354	1814	34.64
2,019,013	1838	−12.60
2,019,073	1898	−48.73
2,019,133	1958	−10.88
2,019,181	2006	42.87
2,019,241	2066	24.73
2,019,301	2126	30.46
2,019,325	2150	7.56
2,019,361	2186	105.91
2,020,008	2198	69.14
2,020,068	2258	103.35
2,020,140	2330	23.73
2,020,176	2366	−10.57
2,020,188	2378	−21.32

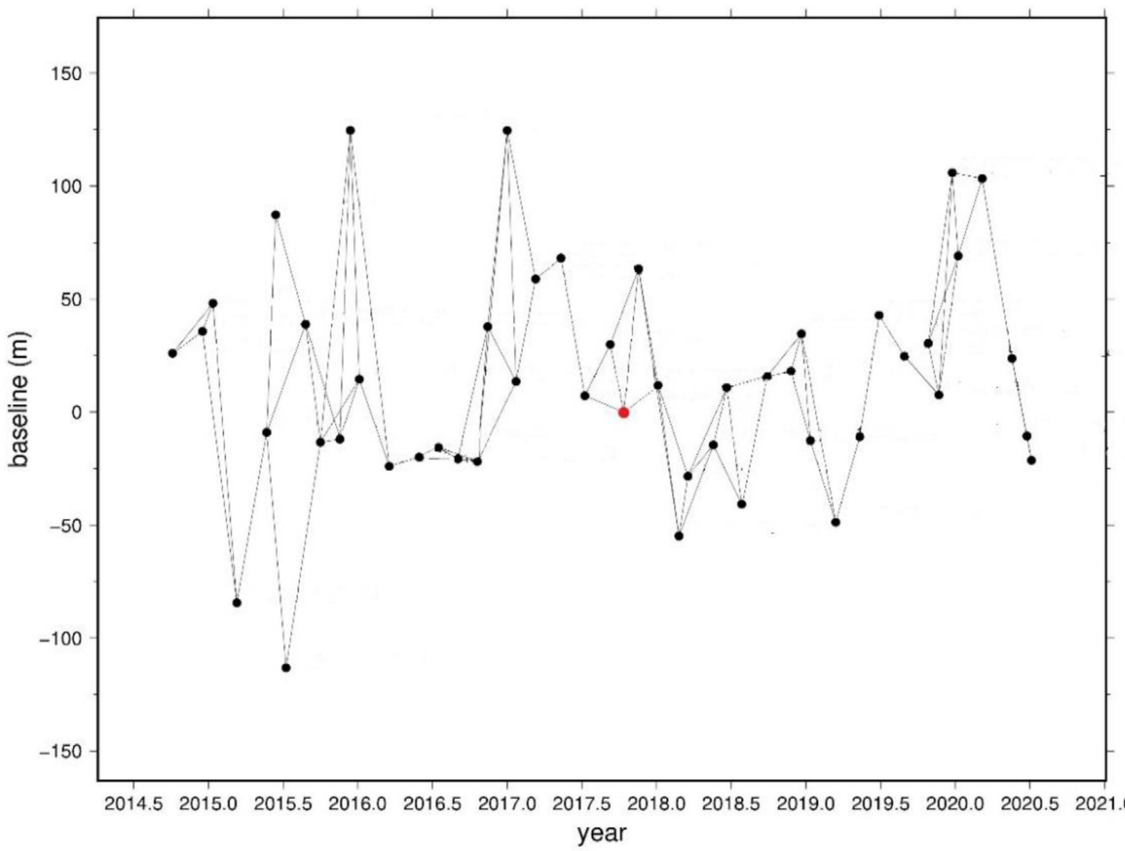

Fig. 4. Spatial and temporal baseline graph for radar data. October 15, 2017, indicates the super master image.

the SBAS algorithm is to minimize the geometric decorrelation of the interferograms through small baselines [7,23,24]. A few studies [7,25–27] have proven that these techniques could identify coherent points in wide regions, especially in nonurban areas, e.g., reclaimed grounds [7]. Results of studies in the mine of Feng Cheng city, Jiang Xi province, showed that SBAS technology was overcome the coherent problem of the traditional D-InSAR technique [28]. Other studies found interferometry techniques possible for an application related to urban planning [29,30], mining subsidence [31], landslide [32], land deformations in mining [33–36]. An effective way to study the behavior of phenomena through time is the time series (TS) analysis [21] The TS tries to control the temporal decorrelation by atmospheric effects and measures temporary movement on the land's surface by using multi-looking interferograms combination and small baseline temporal selection. Land surface deformations detection carried out by underground mines using Sentinel-1A images in Nanhu mines observed that InSAR is a helpful way to study subsidence in a mine area [36], and the velocity of deformation in the Line of Sight (LOS) in Surabaya was varied from −60 mm/year to +20 mm/year. The maximum subsidence occurred in the coastal area (Northern and Eastern parts), while the maximum uplift occurred in the Surabaya downtown area [37] (Southern and Western parts).

2. Study area

Sangan iron ore mine is the largest and the richest mining area in Iran and the Middle East, that is located at longitude E 60°16′ with latitude N 34°24', an approximate 220-km area, 18 km Northeast of Sangan town, east of Iran (Fig. 1). It has semitropical/arid and semi-alpine. The maximum temperature is about 35 °C in August and the minimum temperature of around −5 °C in January. The rate of rain is around 150 mm per year, and it often occurs in April.

The general stratigraphy of the area includes sedimentary formations and igneous in Oligocene to Precambrian that are covered with a complex of alluvial sediments (Fig. 2). The mass of iron ore in the cycle of sediments mass with Tertiary infiltrative igneous in the mountains of Sangan forms the north

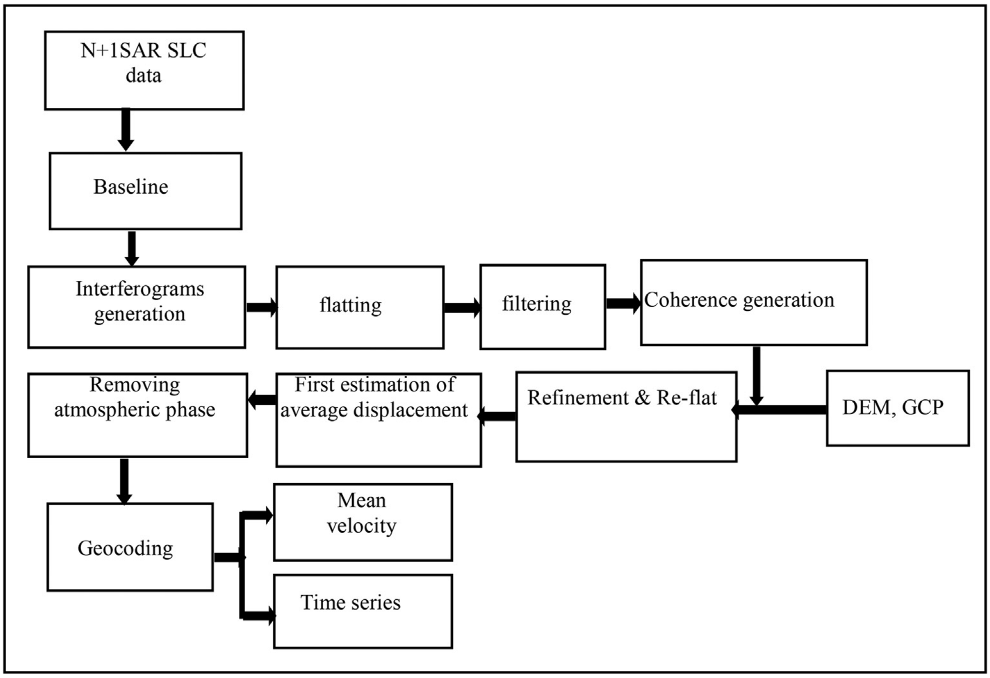

Fig. 5. This flowchart shows the processing steps of Sentinel-1A data.

border of the site. It is believed that the origination of the region's mineralization production is metamorphism, followed by a cycle of significant volcanic in this region that caused a mass of iron ore to appear. The part of the east of the central Iranian Plateau is characterized by plenty of faults and cause in the outcropping of the different layer on both local and regional scales concerning to the proximity to the site. The area landscape is believed to be the end result of the late Cretaceous regression of the inland seas from the Iranian plateau that was subsequently uplifted by a tectonic movement that included volcanic activities. In the period of Neogene, the sea sediments of the Oligocene, due to subsidence of this area, move into the plain and result in the deposition of conglomerates, limestone, and the Red formation.

Geomorphology units of Sangan iron ore mine consist of mountains and piedmonts (erosion pediment, alluvial fans) and plain (Fig. 3).

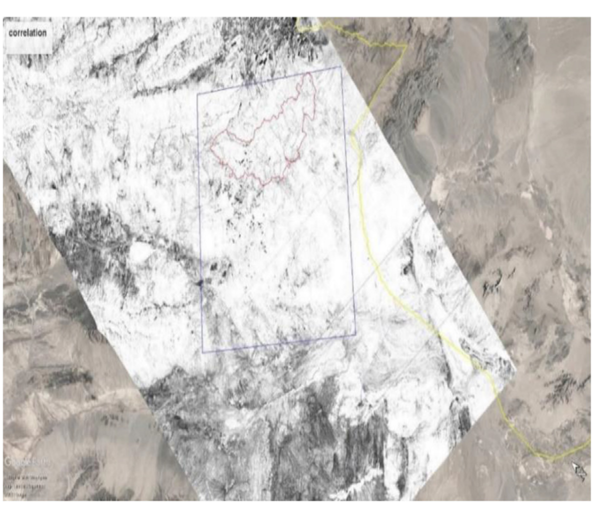

Fig. 6. Sample of coherence images of the interferograms generated from the data pair (2,020,176_2,020,188).

3. Data used and methodology

The SAR images used in this research were acquired by Sentinel-1A. Sentinel-1A images are with a revisiting time of 12 days in IW data acquisition mode and with a swath width of 250 by 180 km. Sentinel-1B satellite data can be used to reduce the intervals between image capture periods; it is reduced to 6 days. Sentinel-1 has launched on April 4, 2014 by European Space Agency (ESA). In this research, data used considering the accessibility of data for Sangan mine consist of 48 Sentinel-1A C-band SAR images with one sub swaths, IW, SLC with incidence angle 43°, descending orbit track, vertical polarization (VV), during the period of October 7, 2014–July 7, 2020, were downloaded of ESA website for this study (Table 1) (HTTPS://sci-hub.copernicus.eu/gnss/#/home). SRTM DEM (Shuttle Radar Topography Mission Digital

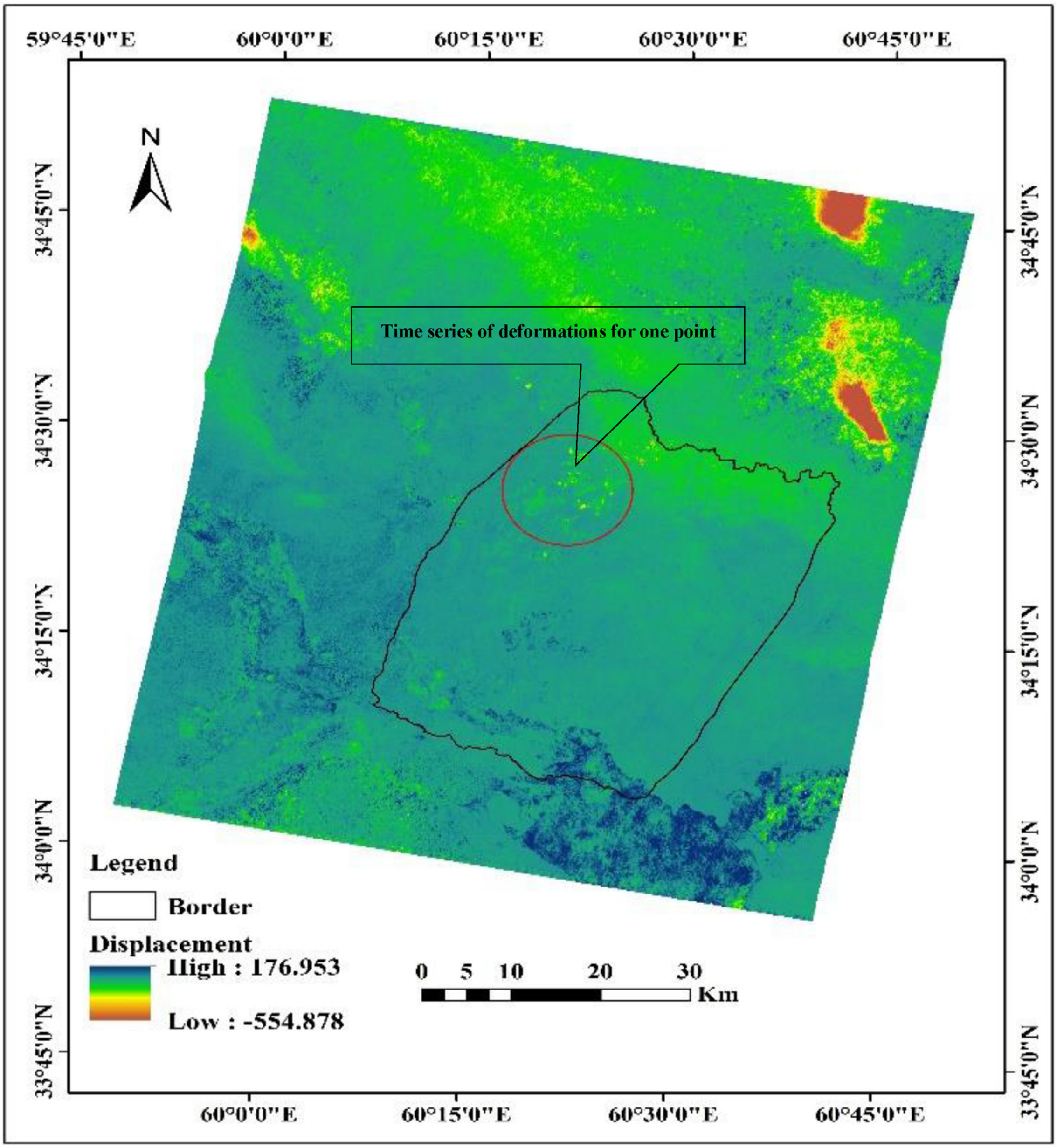

Fig. 7. The locations of maximum deformations caused by mining are highlighted by solid red circles.

Elevation Model) with a resolution of 30 m was used to topography phase error. The images were co-registered with a vertical baseline of fewer than 150 m and a temporal baseline of fewer than 100 days. The Spatial and temporal baseline graph in this image is shown in Fig. 4. The first step in this process is to generate about 81 interferogram pairs with good coherence. Adding more interferograms to the InSAR analysis can be challenging due to several processing issues. One major issue is the computational demand for processing a large dataset of interferograms. The InSAR analysis involvesprocessing pairs of radar images acquired at different times, and the more pairs of images that are processed, the larger the dataset becomes. Processing a large dataset of interferograms can be computationally intensive and time-consuming, requiring significant resources such as high-performance computing systems.

The topographic phase was removed using digital elevation models (SRTM DEM 30 m), and the phase term was removed using adaptive filtering and multi-looking (Averaging two pixels in range and 10 pixels in azimuth). After that, the topography was removed. Their remaining phase was mainly phase-related land surface deformations

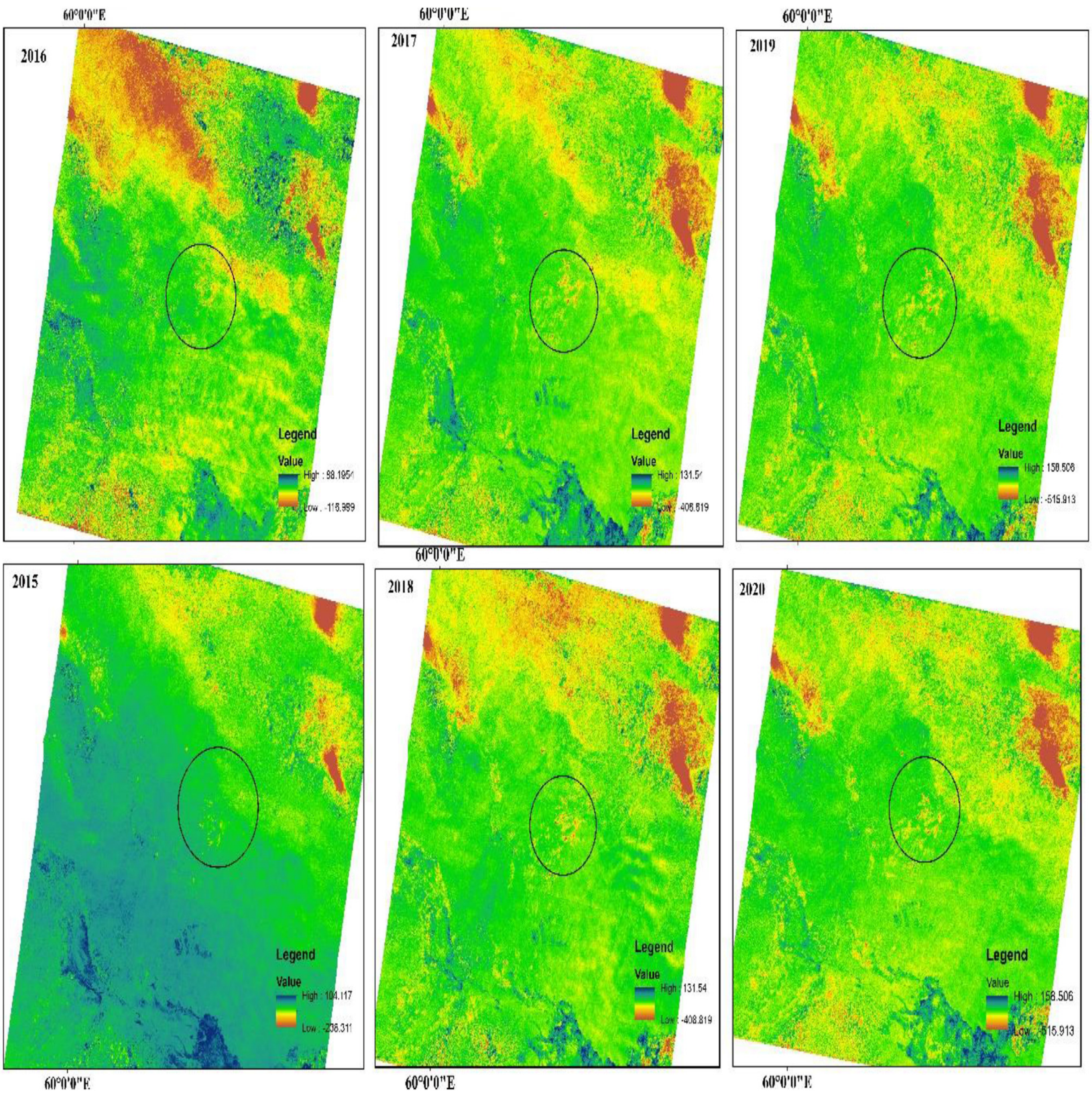

Fig. 8. Black circles are the study area, deformations rates from 2015 to 2020.

and atmospheric and orbital errors. For unwrapping the phase, a minimum cost flow (MCF)) phase unwrap technique was used. We created interferograms for the selected image pairs using the InSAR processing system in GMTSAR (Generic Mapping Tools) software under Linux Ubuntu 16.04 OS. Finally, time-series using the SBAS technique retrieval of displacement deformations based on the unwrapped and corrected phase was conducted. The SBAS flowchart showed in Fig. 5. The reason why we do not use all available images from the monitoring period is as follows. Some images of the study area are corrupted and unavailable, and our computer configuration is not powerful enough.

4. Results and discussion

In this research, we employed SBAS-InSAR, as explained above, which allowed us to discover the deformation rate in the Sangan Iron Ore Mine. The mining area suffering land deformation was identified first before InSAR time-series data processing. After the identification of the mining site, We used

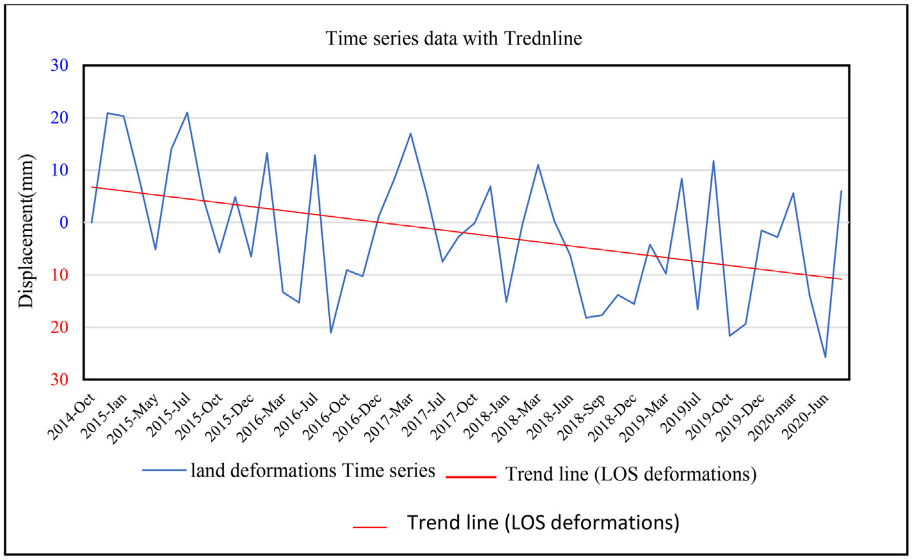

Fig. 9. Time series of deformations for one point.

Fig. 10. Dust of mining activities and wind erosion in the study area.

the 48 scenes of SLC Sentinel-1A images, Interferometric Wide (IW) swath mode acquired along descending, spanning the period from October 7, 2014–July 7, 2020, to estimate the land deformation in Sangan mine. The image from October 15, 2017, was finally identified as the super master image, and the remaining images were paired with this master image for interferometric processing, which resulted in 81 pairs of interferometric images. There are 81 interferograms generated with a temporal baseline of fewer than 100 days and a spatial baseline of less than 150 m, as shown in the baseline graph (Fig. 4). The coherence of area was used to select the high-quality interferograms for the SBAS method, and an example of coherence maps is given in Fig. 6.

Taking 0.5 as the coherence threshold, the average annual deformation in the LOS direction was obtained. The selection threshold of coherent points is lowered to obtain a denser cloud of point targets, which is suitable for a small deformation area. Radar can measure in its LOS or slant-range direction. Line of sight shows the direction/distance between the sensor and the target. The time series cumulative displacement has been established from 2014 to 2020. After the Sentinel-1A satellite data is processed following the above method, a map of the Line of Sight deformation rate from October 2014 to July 2020. The displacement rates in the line-of-sight (LOS) direction for C-band Sentinel-1 datasets are shown in Fig. 7. The results showed that the deformation had caused exacting changes in the topography of the surface. The mean deformation rate is −30 to −40 mm/yrs, and the cumulative displacement rate is attributed to about −30 to −120 mm in the LOS direction. From the observed displacement pattern, surprisingly, the apex and middle alluvial fan parts of the region show high amounts of displacement, which indicates high-stress build-up in the region, and the most deformations occurred in the apex of the alluvial fan (Fig. 7). The time-series deformation of the Sangan iron ore mine is shown in Figs. 8 and 9. During the observed period, all the mining sites suffered significant deformation, and the deformation of each mining site started at different moments, which indicates that mining activities were carried out in all mining areas during the observation period, and the scale of mining activities and working hours varied and deformations over time are increasing.

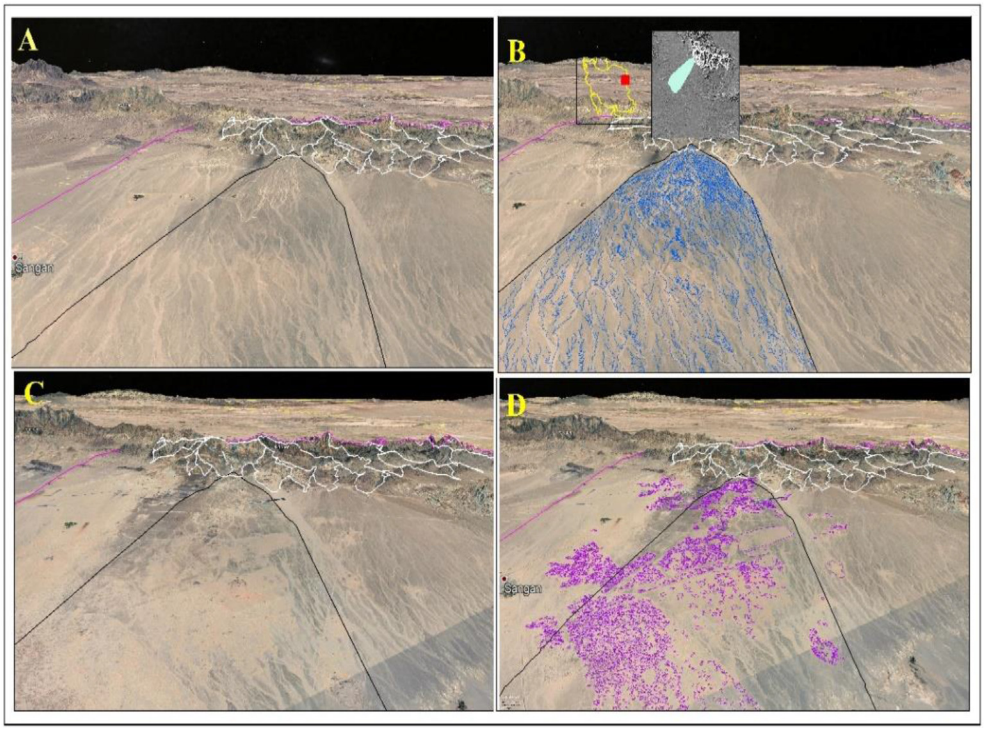

Fig. 11. The Google Earth view of placer mines (A, B) The blue color of the streams before mining activities and in parts (C, D); the violet color is waste dumps after mining(the same area of streams in part A, B).

The results indicate that the surface deformation in the study area region is unstable and rapid, and the displacement increased during the period from 2016 to 2020. These displacements and disturbances have affected geomorphic forms and processes, for example, increased wind erosion (dust) (Fig. 10) and water erosion, slope processes, stream sediment load, and the phenomenon of dust in the area and around.

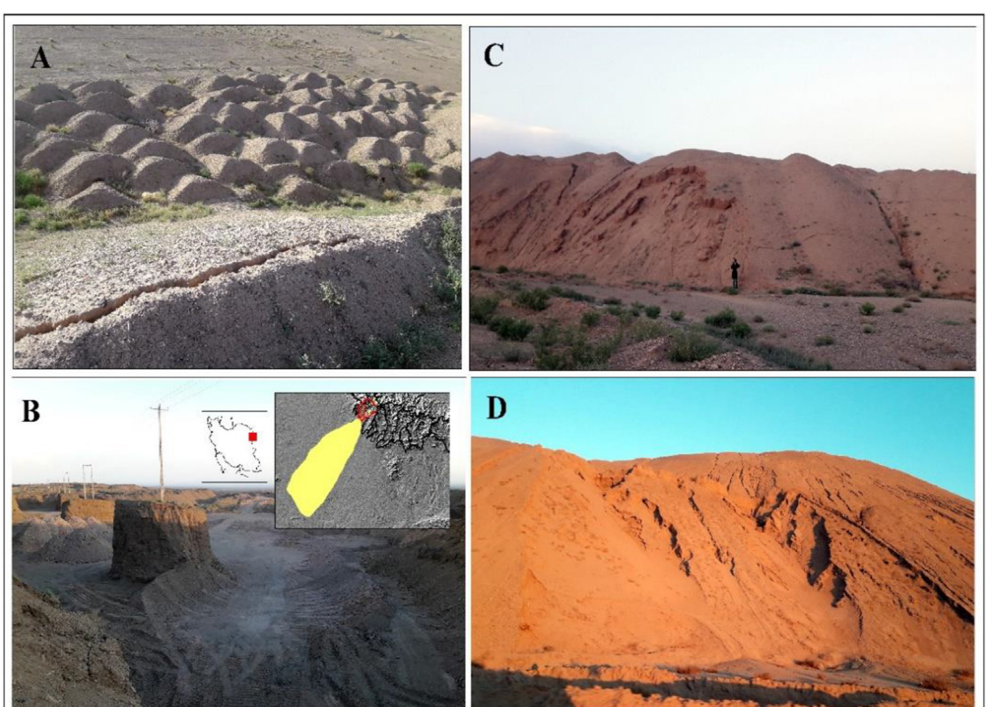

Fig. 12. Deformation effects of mining activities: waste dump of mine and geomorphic processes on it like landslide and erosion (photo by Mahvash Naddaf).

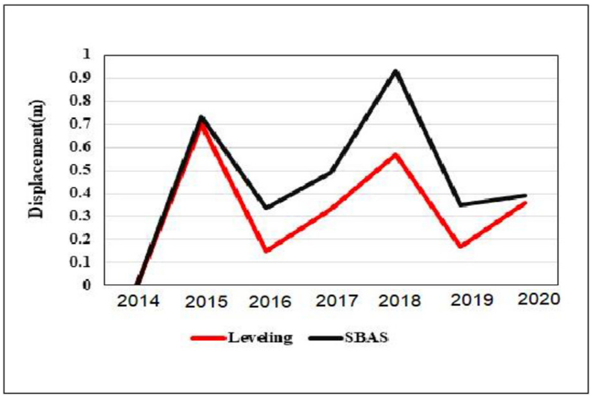

Fig. 13. Comparison between SBAS technique and leveling data.

According to studies and observations, it can be seen that the main effects in the geomorphology of the area are the disruption of the drainage network pattern. The streams developed in two steps: before the mining activity in 2005 at the pre-mining; after mining activity from 2010 to 2020 with the streams based on ditches and gullies (Fig. 11). Waste dumps have changed the direction of streams as well as increased and changed the sedimentary load of streams, changing the profile and changing shape. Also, in the waste dumps, processes such as falling and landslides are occurring. These indicate severe and intermittent changes that have occurred in extraction and waste dumps (mineral extraction and waste dumps) over the years (Fig. 12).

After creating the deformation map, it is suitable to evaluate the InSAR of deformation measurements. Because the mining authority has not conducted field measurements, we could not perform an external reliability assessment for displacement monitoring. We collected the leveling data to confirm the results of SBAS. Because there are no external measurements for the processed period in plain, we had to use a few geodesy data leveling data in the mountain for evaluation. Then the results were evaluated by data leveling (Fig. 13). It has been observed that approximately the same area has the leveling value. However, there may be some errors because the nature of the impression is different. In leveling data, the height changes are measured for one point, but in interferometry, the average rate is from points adjacent to each other.

5. Conclusion

In this research, surface deformations of Sangan mine in East Iran were estimated by the SBAS technique for the period of 2014–2020 using the Sentinel-1 A data. More specifically, our analysis suggests that the mean surface deformation of approximately 75% of the study area ranges from −20 to −35 mm/yr and has a deformation rate of ±120 mm/yr. Our results reveal that the majority of the displacement is observed proximal to the mountain exit. This facilitates areas experiencing higher deformation. This will aid in the denudation of the drainage network and aggravation of geomorphological hazards. We concluded velocity and displacement obtained in the study would be helpful for Geomorphologists. Sentinel-1 A images are more suitable for the detection of fast deformations in open-cast mines area than other mid-spatial resolution SAR satellites data due to their shorter revisiting period. Future research can improve the findings of this research by monitoring long-time deformations in combination with more accurate satellite data. MT-InSAR (Multi-temporal InSAR) is used to extract time series and for deformation rate by means of a network of several acquisitions. In this paper, the deformation measurement results based on the SBAS technique can use as a theoretical basis for environmental restoration in mining areas. This research provides important guidance for the management of mining areas. Generally, surface mining occurs with rapid and significant changes, and InSAR applied in mining areas is good, but only in zones with no significant deformation rates. In open mining, the surface roughness may change over time due to mining activities, making it more difficult to obtain accurate data. However, InSAR can still be a valuable tool for monitoring ground deformation in open mining. However, it is important to be aware of these limitations and to use InSAR data in conjunction with other monitoring techniques to obtain a more complete understanding of the mining activities.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

This research received no external funding.

Conflicts of interest

The authors declare no conflict of interest.

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