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Remote, safe and cost-efficient observations and assessment of geohazard subsidence risks for Kazakhstan energy industry (case study: Tengiz oilfield)

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ABSTRACT: Tengiz oilfield was selected as a study area for the present research because of its historically reported continuous subsidence and limited studies for this area during recent years. This study focused on the quantitative assessment of the vertical displacement velocities retrieved using Sentinel-1 and Cosmo-SkyMed synthetic aperture radar images for the Tengiz oilfield. The small baseline subset time-series technique was used for the interferometric processing of radar images acquired for the period of 2018–2020. The geospatial and statistical analyses allowed to determine the existing hotspots of the subsidence processes induced by oil extraction in the study area. Ground deformation measurements derived from the Sentinel-1 and COSMO-SkyMed satellite missions showed that the Tengiz oilfield continuously subsided during 2018–2020 with the maximum annual vertical displacement velocity around −77.4 mm/y and −71.5 mm/y, respectively. The vertical displacement velocities derived from the Sentinel-1 and the COSMO-SkyMed images showed a good statistical relationship with $R^2 \geq 0.73$ and RMSE ≤3.68 mm. The cumulative vertical displacement derived from both satellites for the most subsiding location also showed a good statistical relationship with R^2 equal to 0.97 and RMSE = ± 4.69. The observed relative differences of measurements by both satellites were acceptable to determine the ongoing vertical surface displacement processes in the study area. These studies demonstrated a practical novelty for the petroleum industry in terms of the comparative assessment of surface displacement measurements using time-series of medium-resolution Sentinel-1 and high-resolution COSMO-SkyMed radar images.

1 INTRODUCTION

Tengiz oilfield is located at the coast of the Caspian Sea with low-lying wetlands. The recent successful studies by (Bayramov et al. 2021; Grebby et al. 2019 and Orynbassarova 2019) proved that the Tengiz oilfield was under the impact of ground deformation processes induced by the petroleum and gas operational activities.

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Nowadays, industry significantly benefits from the ground deformation mapping as one of the important advancements for the surveillance programs of onshore oil and gas reservoirs. It is well known that the interferometric technologies were verified as effective for the measurement of the sensor-to-target line of sight projection of the ground deformation mapping of large onshore reservoirs rather than traditional in-situ measurements using geodetic tools (Zhou et al. 2006; Mirzaii et al. 2019). The studies by Grebby et al. (2019) and Orynbassarova (2019) clearly indicated the vertical displacements caused by oil and gas exploitation in the Tengiz oilfield during 2004-2009 and 2016-2017, by using Envisat and Sentinel-1 radar images, correspondingly. The investigations by Grebby et al. (2019) and Orynbassarova (2019) applied the Intermittent Small Baseline Subset (ISBAS) method from Sowter et al. 2013 which contributed to the determination of the continuously increasing cumulative vertical displacement (maximum of -79.3 mm/year) in the Tengiz oilfield during 2016–2017.

To the extent of our awareness, there have been few publically accessible studies on the multi-satellite monitoring of vertical displacements in the Tengiz oilfield, in particular with the focus on the comparative assessment of vertical displacements derived from multiple Sentinel-1 and Cosmo-SkyMed Synthetic Aperture Radar (SAR) imagery.

Our research specifically focused on the assessment of vertical displacements derived from COSMO-SkyMed and Sentinel-1 SAR imagery using SBAS multi-temporal interferometric technique and geostatistical interpolation techniques followed by the cosine corrections to derive vertical movements from LOS measurements. The primary advantage of the present research is to quantitatively examine the differences in vertical displacement measurements using C-band Sentinel-1 and X-band Cosmo-SkyMed SAR imagery since in-situ geodetic measurements were not accessible for the present research. The detailed goals of the present research are as follows:

1) SBAS-based detection of vertical displacement hotspots using COSMO-SkyMed and Sentinel-1 imagery acquired during 2018–2020
2) Quantitative analyses of the vertical displacement velocities and cumulative vertical displacement derived from Sentinel-1 and COSMO-SkyMed satellite images
3) Determination of spatial relationships between the detected patterns and the hotspots of vertical displacements, wells and faults

2 DATA PROCESSING

2.1 *Research area*

Tengiz oilfield is one of the largest in the world and it is located at the coast of the Caspian Sea with an area of 2,500 km2 (Figure 1a and b). The climate in the study area is semi-arid with temperature range −30 °C - 40° in summer and winter, respectively. The average annual precipitation is in the range of 100–200 mm (Klein et al., 2012). Tengiz field is located in the seismically active region of Kazakhstan. The seismic faults derived from (Anissimov et al. 2000) are indicated in Figure 1. According to (Grebby et al. 2019), the reservoir is estimated to be around 25 billion barrels of oil and is located at the depth of 3885–5117 m. High pressure with large proportion of gas was observed in the oil coming out of wells. The production is estimated to be 720,000 barrels per day. Sour gas injection enhanced oil recovery method is used in the Tengiz oilfield (Bealessio et al. 2020).

2.2 *Quantitative assessment of vertical displacement in the Tengiz Oilfeld using SBAS processing of Sentinel-1 and Cosmo-SkyMed images*

Sentinel-1 A/B TOPS with C-band (5.6 cm wavelength and 5.4 GHz) images from the European Space Agency (ESA) and COSMO-SkyMed (CSK) with X-band (3.1 cm wavelength and 9.6 GHz) from the Italian Space Agency were used for the present study to assess the vertical displacement velocities and cumulative vertical displacement in the Tengiz oilfield. The extents of the Sentinel-1 and COSMO-SkyMed imagery are presented in Figure 1b. 96 Sentinel-1 images were acquired on descending Path 35, Frame 441, Absolute Orbit 30,557 in the TOPSAR Interferometric Wide Swath (IW) mode, with VV + VH Polarization between 1 January 2018 and 31 December 2020

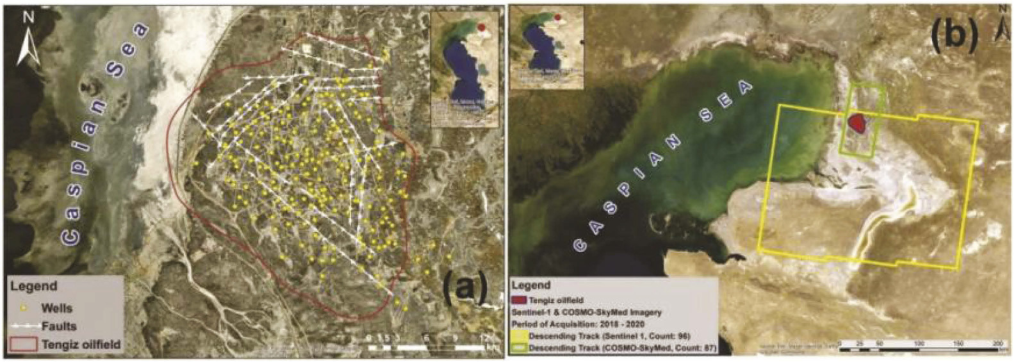

Figure 1. (a) Tengiz oilfield with the representation of wells and faults; (b) Extents, count and acquisition period of Sentinel-1 and COSMO-SkyMed imagery.

(Figure 1b). VV polarization band of Sentinel-1 was used because of a higher coherence (Imamoglu et al. 2019). Sentinel-1images in wide-swath mode provide a wide coverage of about 250 km with a range resolution of 5 m and an azimuth resolution of 20 m (Yang et al. 2019).

87 COSMO-SkyMed images were acquired on descending Frame 2, Absolute Orbit 39,000 in the interferometric StripMap HIMAGE mode with HH polarization between 1 January 2018 and 31 December 2020. HH polarization band of COSMO-SkyMed that was only available had been used for the present research. COSMO-SkyMed images in StripMap Himage mode provide coverage of about 40 km with a range resolution of 3 m and an azimuth resolution of 3 m (Tapete and Cigna 2019) (Figure 1b). Descending tracks of Sentinel-1 and COSMO-SkyMed satellite images provided a complete coverage of the Tengiz oilfield.

SBAS - based interferometric processing technique was used for the assessment of the vertical displacement. SBAS workflow is presented in Figure 2 with the following processing steps: creation of a connection graph, definition of AOI, generation of interferograms, refinement and reflattening, first inversion, second inversion and geocoding (Loesch and Sagan 2018; Sarmap 2021).

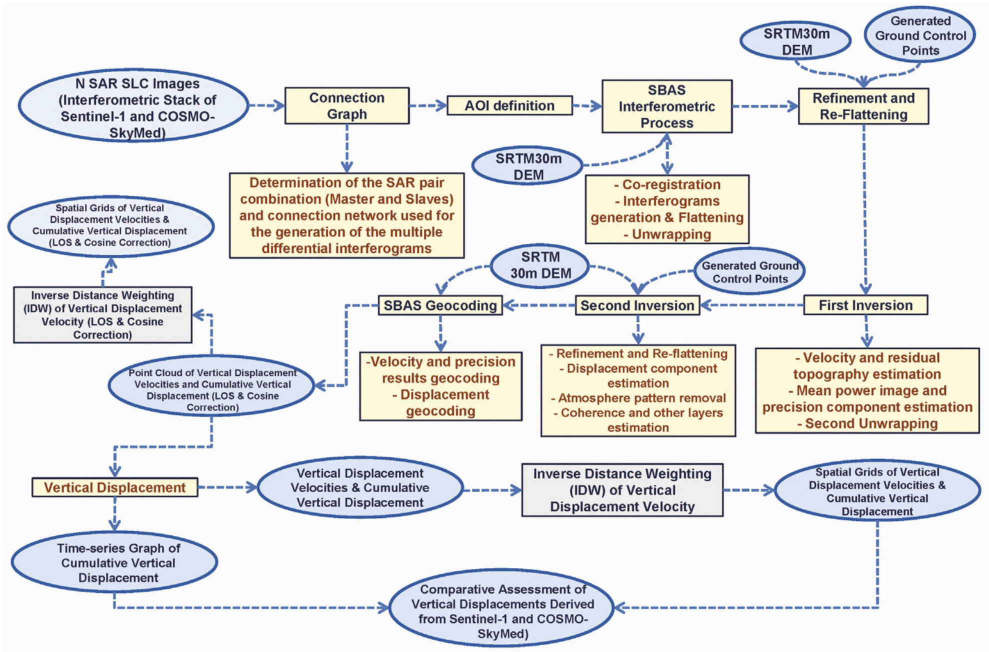

Figure 2. Workflow of SBAS interferometric processing followed by the cosine correction for the assessment of vertical displacements and spatial interpolations.

3 RESULTS

LOS displacement velocity derived from the Sentinel-1 radar satellite images was observed to be in the range of − 58.9 - 22.7 mm/y (Figure 3a). The vertical displacement velocity derived through the division of the LOS displacement rates by the cosine of the radar incidence angle is presented in Figure 3b with the range of −77.4 - 29.4 mm/y. The spatial distribution histogram of the measured LOS and vertical displacement velocities derived from the cosine corrections are presented in Figure 3c. It is possible to clearly observe the prevailing number of pixels with negative values which confirms the ongoing subsidence in the Tengiz oilfield.

The hotspot of significant subsidence can be observed at the crossing of profile lines in Figure 4a. The same location was observed to be as the most subsiding. As it is possible to observe in Figure 4b, the maximum annual subsidence velocity along the profiles reaches about −70 mm/y. The cumulative vertical displacement is shown in Figure 5a with the range of −243.7 - 79.9 mm. The maximum cumulative vertical displacement along the profiles on 23 December 2020 reaches − 235 mm (Figure 5b).

Unfortunately, because of no accessibility to the historical in-situ high-precision geodetic measurements in the present research, it was not possible to validate the reliability and accuracy of the SBAS measurements derived from the Sentinel-1 images. Therefore, it was considered to use the COSMO-SkyMed images for the cross-validation of measurements from both satellites. The processed area of the COSMO-SkyMed images was limited to the subsiding hotspots derived from the processing of the Sentinel-1 images. The spatially interpolated vertical displacement velocity derived from the COSMO-SkyMed images is presented in Figure 6a. Figure 6b presents the spatial distribution of SBAS measured points derived from the COSMO-SkyMed and the Sentinel-1 images. These points with measured vertical velocities were used in the interpolation of spatial grids used in the comparative analysis (Figure 6a). The enhanced view of the vertical displacement velocity derived from the COSMO-SkyMed images and profile lines are presented in Figure 6c. The histogram of negative vertical displacement velocities derived from the COSMO-SkyMed images is presented in Figure 6d. This implies that the SBAS analyses using the COSMO-SkyMed images also showed the subsidence processes in the same hotspot detected by the processing of the Sentinel-1 images.

The profiles of the vertical displacement velocities derived from the Sentinel-1 and the COSMO-SkyMed images are presented in Figure 6c and Figures 7a–d. As it is possible to observe, the vertical displacement velocities derived from the Sentinel-1 and the COSMO-SkyMed images for the Profile 1 showed a good statistical relationship with R^2 equal to 0.93, p-value < 0.05, RMSE equal to ±2.86 (Figures 7a and b). Good statistical relationship was also observed for the Profile 2 with R^2 equal to 0.73, p-value < 0.05, RMSE equal to ±3.68 (Figures 7c and d). The standard deviation of the phase calculated over the profiles 1 and 2 was observed to be 8.9 for profile 1 and 7.9 for the profile 2 (Figures 7a and c).

The location for the maximum subsidence derived from the Sentinel-1 images is presented in Figure 8a. The cumulative vertical displacement derived from the Sentinel-1 and the COSMO-SkyMed images for the most subsiding location are presented in Figure 8b. The cumulative vertical displacement in the most subsiding location reaches around 245 mm on 23 December 2020 (Figure 8b). The regression analysis between the cumulative vertical displacements derived from the Sentinel-1 and COSMO-SkyMed images for the most subsiding location showed a strong statistical relationship with R^2 equal to 0.97. This was also reflected in RMSE = ± 4.69 and p-value < 0.05. This allows to conclude that SBAS produced identical results from the Sentinel-1 and the COSMO-SkyMed images. It is obvious that the ground deformation measurements from the COSMO-SkyMed images are more detailed because of the higher spatial resolution of images.

Since the hotspot of the most subsiding areas is not anyhow spatially related to the concentration of wells, it is possible to assume that the primary factors controlling the vertical displacements in the Tengiz oilfield are the oil and gas extraction industrial processes and natural subsurface tectonics. However, it is possible to observe that a number of wells are located within the detected hotspot of the subsidence in Figure 8a. The oil terminal is located outside of the subsidence hotspot (Figure 1a; Figure 8a) and it is obviously less vulnerable to the potential geohazards.

Besides these areas are crossed by faults which might be subject to the potential reactivation (Figure 8a). Hence, some of the wells located within the detected subsidence hotspot should always be prioritized for the regular geotechnical and geohazard risk assessment.

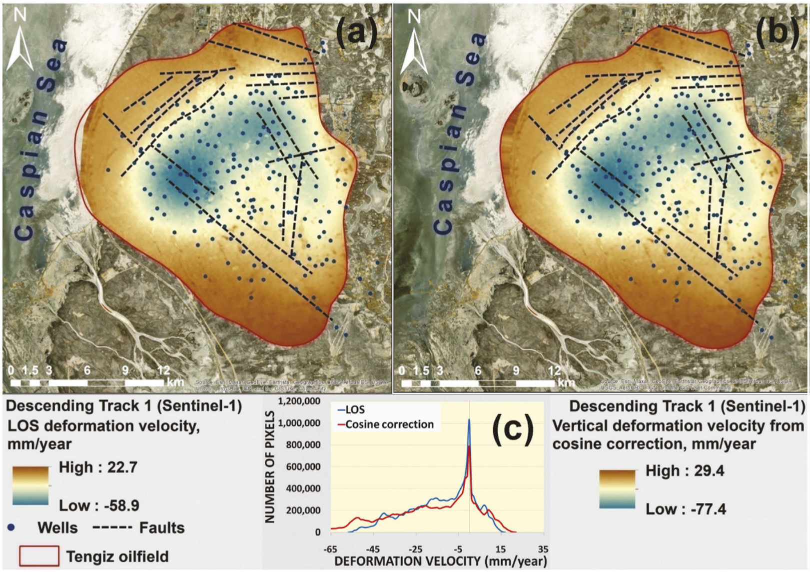

Figure 3. (a) LOS and (b) vertical displacement velocity from cosine correction of the Tengiz oilfield; (c) Histogram of LOS and vertical displacement velocity.

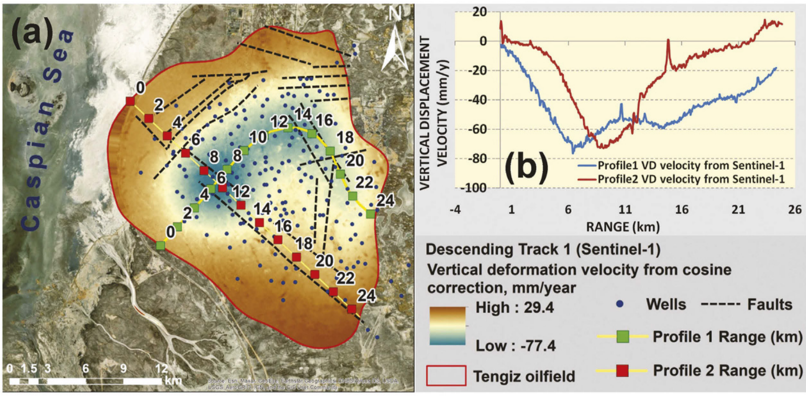

Figure 4. (a) Map of vertical displacement velocity derived from the Sentinel-1 images with the indication of profile lines; (b) profile lines of vertical displacement velocities.

4 DISCUSSION

The assessment of the vertical displacement velocities and cumulative vertical displacement derived from the Sentinel-1 and the COSMO-SkyMed images showed a good statistical relationship. This allows to assume that the measurements by both satellites are reliable. The present research results also exhibit shortcomings related to the non-accessibility to the historical in-situ geodetic measurements to verify the accuracy of the measurements. Therefore this study used both Sentinel-1 and COSMO-SkyMed images to cross-validate the achieved results from both satellites. The qualitative judgment for the verification of the present research

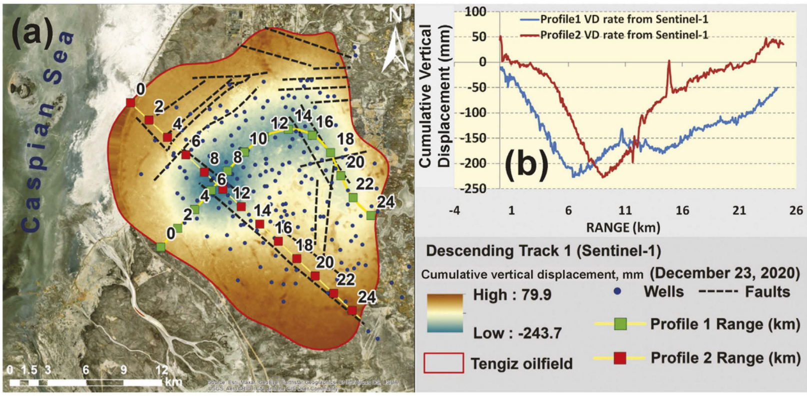

Figure 5. (a) Map of cumulative vertical displacement derived from the Sentinel-1 images with the indication of profile lines; (b) profile lines of cumulative vertical displacement.

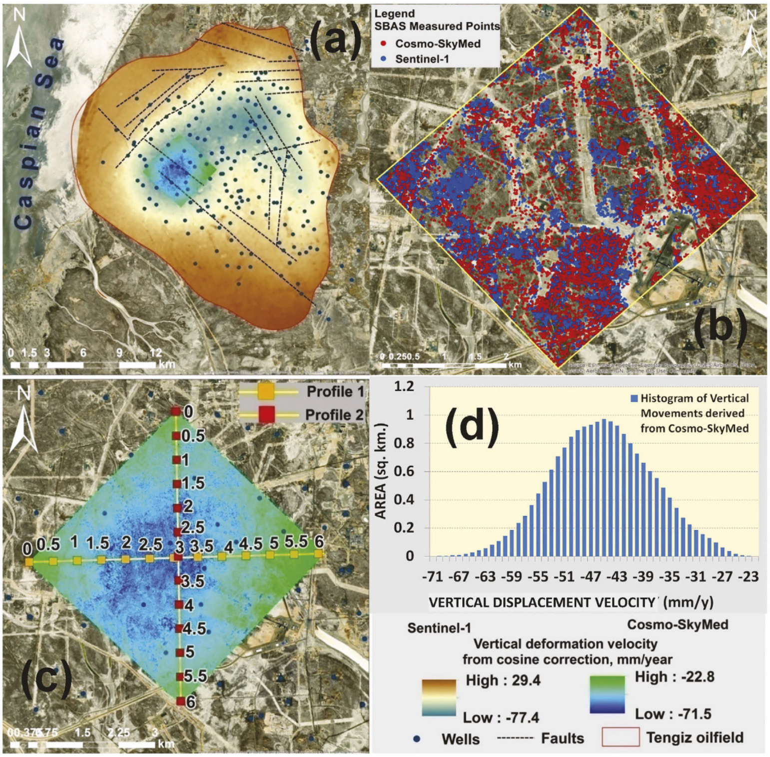

Figure 6. (a) Map of the spatially interpolated vertical displacement velocity derived from the Sentinel-1 and COSMO-SkyMed satellite images; (B) SBAS measured points from the Sentinel-1 and COSMO-SkyMed satellite images used for the spatial interpolation; (C) profile lines of vertical displacement velocity derived from the COSMO-SkyMed images; (D) histogram of vertical displacement velocities derived from the COSMO-SkyMed satellite images.

results was also based on the previously published studies which also observed and detected continuous subsidence processes in the Tengiz oilfield (Del Conte et al. 2013; Comola et al. 2016; Grebby et al. 2019; Orynbassarova 2019; Bayramov et al. 2021). The identical spatial deformation patterns and trends with a maximum subsidence rate rising up-to −79.3 mm/year were observed in the previous studies by Grebby et al. 2019 and Orynbassarova 2019.

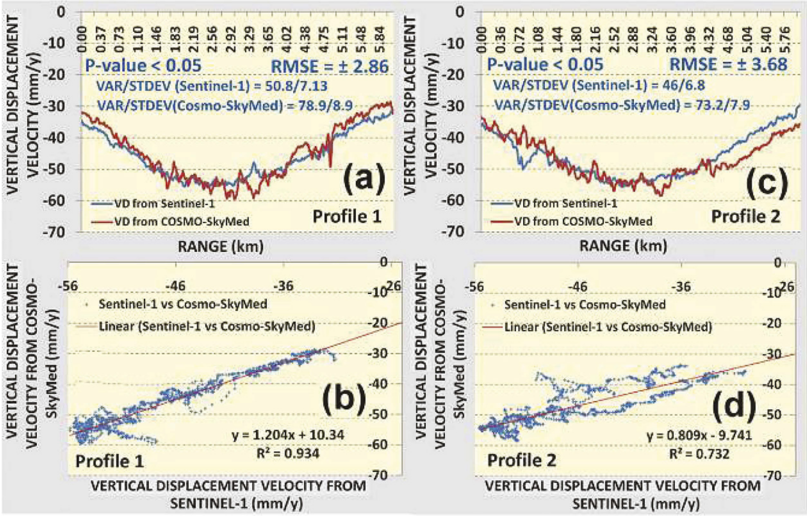

Figure 7. Vertical displacement velocity derived from the Sentinel-1 and COSMO-SkyMed satellite images for: (a) profile 1 VD, (b) regression analysis between vertical displacement velocities derived from the Sentinel-1 and COSMO-SkyMed satellite images for profile 1; (c) profile 2 VD, (d) regression analysis between vertical displacement velocities derived from the Sentinel-1 and COSMO-SkyMed satellite images for profile 2.

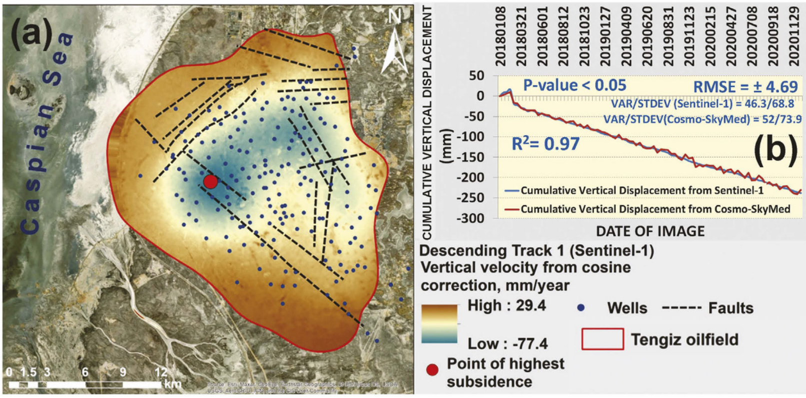

Figure 8. (a) Location of the most subsiding location based on the cumulative vertical displacement derived from the Sentinel-1 images; (b) regression analysis between the cumulative vertical displacements derived from the Sentinel-1 and COSMO-SkyMed satellite images for the most subsiding location.

It is quite difficult to judge about the criticality level of the ongoing and increasing vertical displacement velocities and cumulative vertical displacement of the Tengiz oilfield subsidence in the relationship to the petroleum and gas industry standards for the effective risk management.

However the previous studies by (Mahajan et al. 2018) indicated that the reservoir compaction cases in Oman resulted in the well damages, well integrity, and subsidence damage to the facilities of surface tremors because of fault reactivation. As it was possible to observe in the present studies, around 15 wells of the Tengiz oilfield are located in the detected subsidence hotspot from two satellites. Besides, it is necessary to emphasize the fact of the increasing subsidence velocity that was also well spotted by the present research and previous studies of (Grebby et al. 2019). The application of Sentinel-1 or COSMO-SkyMed images should be selected depending on the scale of analysis, required density and precision of measurements.

5 CONCLUSION

The present research compared the vertical displacements derived from the Sentinel-1 and COSMO-SkyMed radar images collected during 2018-2020 for the Tengiz oilfield.

- The vertical displacement velocities and cumulative vertical displacement derived from the Sentinel-1 and COSMO-SkyMed images showed good agreement. The vertical displacement velocities derived from the Sentinel-1 and COSMO-SkyMed images showed a good statistical relationship with R^2 equal to 0.93, P-value < 0.05 and RMSE equal to ±2.86 for the Profile one and R^2 equal to 0.73, P-value < 0.05 and RMSE equal to ±3.68 for Profile 2. The cumulative vertical displacement derived from the Sentinel-1 and COSMO-SkyMed images for the most subsiding location showed a good statistical relationship with R^2 equal to 0.97, P-value < 0.05 and RMSE = ± 4.69. This allowed to assume that the SBAS measurements from both satellites are reliable and also confirmed the ongoing subsidence processes in the Tengiz oilfield.
- Vertical displacement velocities and cumulative vertical displacement derived from the COSMO-SkyMed images were observed to be more dispersed than from the Sentinel-1 images. This was reflected in the higher sample variance and standard deviation of the vertical displacement values derived from the COSMO-SkyMed mages.
- Ground deformations derived from the Sentinel-1 and COSMO-SkyMed images showed that the Tengiz oilfield subsided during 2018-2020 with the maximum annual vertical displacement velocity around −77.4 mm/y and −71.5 mm/y, respectively. - The detected hotspot of the most subsiding areas was not anyhow spatially related to the concentration of wells. Therefore, it is possible to assume that primary factors controlling the vertical displacements in the Tengiz oilfield are the oil and gas extraction industrial processes and also natural subsurface tectonics.
- The selection among the Sentinel-1 or COSMO-SkyMed images should be decided depending on the scale of analysis, required density and precision of measurements.

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REFERENCES

Bayramov, E., Buchroithner, M., Kada, M., and Zhuniskenov, Y. 2021. Quantitative Assessment of Vertical and Horizontal Deformations Derived by 3D and 2D Decompositions of InSAR Line-Of-Sight Measurements to Supplement Industry Surveillance Programs in the Tengiz Oilfield (Kazakhstan). Remote Sensing 13, 2579. doi:10.3390/rs13132579.

Grebby, S., Orynbassarova, E., Sowter, A., Gee, D., and Athab, A. 2019. Delineating Ground Deformation over the Tengiz Oil Field, Kazakhstan, Using the Intermittent SBAS (ISBAS) DInSAR Algorithm. Int. J. Appl. Earth Observation Geoinformation 81, 37–46. doi:10.1016/j.jag.2019.05.001.

Orynbassarova, E. 2019. Improvement of the Method of Integrated Preparation and Use of Space Images in Tasks of Assessment of Sedimentation of Industrial Surface in the Conditions of Operation of Tengiz Oil and Gas field PhD Dissertation. Satbayev University.

Zhou, W., Chen, G., Li, S., and Ke, J. 2006. InSAR Application in Detection of Oilfield Subsidence on Alaska North Slope, in Proceedings of the 41st US Symposium on Rock Mechanics (USRMS), Golden, CO, USA, 17–21 June 2006.

Mirzaii, Z., Hasanlou, M., Samieie-Esfahany, S., Rojhani, M., and Ajourlou, P. 2019. Land Subsidence Monitoring in Azar Oil Field Based on Time Series Analysis. Proceedings 18 (1), 2. doi:10.3390/ecrs-3-06190.

Klein, I., Gessner, U., and Kuenzer, C. 2012. Regional Land Cover Mapping and Change Detection in Central Asia Using MODIS Time-Series. Appl. Geogr. 35, 219–234. doi:10.1016/j.apgeog.2012.06.016.
Anissimov, L., Postnova, E., and Merkulov, O. 2000. Tengiz Oilfield: Geological Model Based on Hydrodynamic Data. Pet. Geosci. 6, 59–65. doi:10.1144/petgeo.6.1.59.
Bealessio, B. A., Blánquez Alonso, N. A., Mendes, N. J., Sande, A. V., and Hascakir, B. 2020. A Review of Enhanced Oil Recovery (EOR) Methods Applied in Kazakhstan. Petroleum 7 (1), 1–9.
Imamoglu, M., Kahraman, F., Cakir, Z., and Sanli, F. B. 2019. Ground Deformation Analysis of Bolvadin (W. Turkey) by Means of Multi-Temporal InSAR Techniques and Sentinel-1 Data. Remote Sensing 11, 1069. doi:10.3390/rs11091069.
Yang, C., Zhang, D., Zhao, C., Han, B., Sun, R., Du, J., et al. 2019. Ground Deformation Revealed by Sentinel-1 MSBAS-InSAR Time-Series over Karamay Oilfield, China. Remote Sensing 11, 2027. doi:10.3390/rs11172027.
Tapete, D., and Cigna, F. 2019. COSMO-SkyMed SAR for Detection and Monitoring of Archaeological and Cultural Heritage Sites. Remote Sensing 11 (11), 1326. doi:10.3390/rs11111326.
Loesch, E., and Sagan, V. 2018. SBAS Analysis of Induced Ground Surface Deformation from Wastewater Injection in East Central Oklahoma, USA. Remote Sensing 10, 283. doi:10.3390/rs10020283
Sarmap (2021). SBAS Tutorial. Available at: https://www.sarmap.ch/index.php/software/sarscape.
Del Conte, S., Tamburini, A., Cespa, S., Rucci, A., and Ferretti, A. 2013. Advanced InSAR Technology for Reservoir Monitoring and Geomechanical Model Calibration, in SPE Kuwait Oil and Gas Show and Conference. doi:10.2118/167339-ms.
Comola, F., Janna, C., Lovison, A., Minini, M., Tamburini, A., and Teatini, P. 2016. Efficient Global Optimization of Reservoir Geomechanical Parameters Based on Synthetic Aperture Radar-Derived Ground Displacements. Geophysics 81 (3), M23–M33. doi:10.1190/geo2015-0402.1.
Mahajan, S., Hassan, H., Duggan, T., and Dhir, R. 2018. Compaction and Subsidence Assessment to Optimize Field Development Planning for an Oil Field in Sultanate of Oman, in Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, November 2018 (UAE). Paper presented at the Abu. doi:10.2118/192744-MS.