6th Intercontinental Geoinformation Days

igd.mersin.edu.tr

Study of land subsidence induced by oil extraction in the Tengiz oilfield of Kazakhstan using radar interferometry (InSAR)

Emil Bayramov*[1], Manfred Buchroithner [2], Martin Kada [3], Saida Aliyeva [4]

[1] *Nazarbayev University, School of Mining and Geosciences, Astana, Kazakhstan*
[2] *Dresden University of Technology, Institute of Cartography, Dresden, Germany*
[3] *Technical University of Berlin, Institute of Geodesy and Geoinformation Science, Berlin, Germany*
[4] *ADA University, School of Education, Baku, Azerbaijan*

Keywords
SBAS
2D and 3D decomposition
Geospatial
Oil field
Interferometry

Abstract

Our studies focused on the assessment of the surface deformation velocities and cumulative displacements at Tengiz Oilfield in Kazakhstan using the Small Baseline Subset remote sensing technique followed by 3D and 2D decompositions and cosine corrections to derive vertical and horizontal movements from line-of-sight (LOS) measurements. In the present research we applied time-series of Sentinel-1 satellite images acquired during 2018-2020. All ground deformation derivatives showed the continuous subsidence at the Tengiz oilfield with increasing velocity. 3D and 2D decompositions of LOS measurements to vertical movement showed that the Tengiz Oil Field 2018-2020 continuously subsided with the maximum annual vertical deformation velocity around 70 mm. Based on the LOS measurements, the maximum annual subsiding velocity was observed to be 60 mm. The results of the present research will support operators of oil and gas fields and also other types of infrastructure to evaluate the actual differences of InSAR ground deformation measurements against the required standards and the precision of measurements depending on the operational needs, timeframes and availability of radar imagery.

1. Introduction

Tengiz is an oilfield located in NW Kazakhstan's low-lying wetlands along the northeast shores of the Caspian Sea. Recent studies by Grebby et al. (2019) and Orynbassarova (2019) proved that Tengiz Field has been for some time under the long-term influence of subsidence induced by oil and gas production. Monitoring of ground deformation processes at oil and gas fields has several business values for industry since it is one of the critical input parameters for geohazard risk assessment, induced seismicity, geomechanics surveillance programs (reservoir stress, volumetric strain, fault reactivations and dislocation), site safety for fault or landslide reactivation, well failures, environmental assessment, reservoir modelling, enhanced oil recovery (EOR), oil and gas production. Interferometric Synthetic Aperture Radar (InSAR) technology was verified as a more effective technology for the ground deformation monitoring of large oil and gas fields and their infrastructure rather than traditional geodetic measurements of single points (Bayramov et al., 2020a, Bayramov et al. 2020b, Bayramov et al., 2020c, Mirzaii et al., 2019). Even though geodetic measurements have higher accuracy, they do not reflect the large scale of deformation patterns (Shi et al., 2019). However, there have been few publicly accessible studies on the surface deformation characteristics of the Tengiz field in recent years. Therefore, monitoring recent surface deformations over the Tengiz oilfield is of great importance and business value for guiding the continued exploitation there. To the extent of our knowledge, there are also no publicly accessible studies focused on the use of 3D or 2D decomposition techniques to derive vertical and horizontal deformations for the Tengiz field in the recent years. The present studies thus offer practical scientific value and advantages for the petroleum and gas industry.

*Corresponding Author

*(bayramov@nu.edu.kz) ORCID ID 0000-0002-3804-5373

Cite this study

Bayramov, E., Buchroithner, M., Kada, M., & Aliyeva, S. (2023). Study of land subsidence induced by oil extraction in the Tengiz oilfield of Kazakhstan using radar interferometry (InSAR), 6, 162-167, Baku, Azerbaijan

Our research focused on the quantitative assessment of the surface deformation velocities and rates and their natural and man-made controlling factors at the Tengiz oilfield using Small Baseline Subset (SBAS) remote sensing and geostatistical interpolation techniques followed by 3D and 2D decompositions and cosine corrections to derive vertical and horizontal movements from LOS measurements. Sentinel-1 satellite images acquired from ascending and descending tracks during 2018-2020 were used in our studies. The detailed research goals are as follows:

(1) Determination of ground deformation velocities and rates at the Tengiz oilfield over the period of 2018-2020 using SBAS remote sensing techniques followed by 3D and 2D decompositions and cosine corrections to derive vertical and horizontal east-west and north-south movements from LOS measurements

(2) Detection of vertical and horizontal ground deformation hotspots

(3) Quantitative comparison of the ground deformation velocities and rates derived from LOS, 3D and 2D decomposition and cosine correction measurements

(4) Assessment of the spatial relationships between the detected patterns of vertical and horizontal ground deformations, man-made oil field exploitation and natural tectonic processes

(5) Provision of recommendations to operators of oil and gas fields and other types of petroleum infrastructure.

2. Method

2.1. Study Area

The Tengiz oilfield was discovered in 1979 and it is one of the largest discoveries worldwide in recent history. It is located in north-western Kazakhstan's low-lying wetlands along the northeast shores of the Caspian Sea (Figure 1) and covers an area of 430 km2, being 19 km wide and 21 km long. It is located 150 km south-east of the city of Atyrau which is considered to be the main transport hub for Tengiz oil. Tengiz field has recoverable reserves estimated at between six billion and nine billion barrels. However, the reservoir is estimated to contain around 25 billion barrels of oil and is located at the depth of 3885-5117 m (Grebby et al., 2019). The oil comes out of wells hot at high pressure and with a large proportion of gas. Current oil production is 720,000 barrels per day. The region has a semi-arid climate, with temperatures decreasing to –30°C in winter and reaching up to 40C in summer. The average annual precipitation varies in the range of 100 - 200 mm (Klein et al., 2012). The terrain of the study area is flat, but with regular depressions formed as a result of seasonal snow melts and rainfalls (Grebby et al., 2019). The sour gas injection enhanced oil recovery method is used at the Tengiz oilfield (Bealessio et al., 2020). The Tengiz field is located within the seismically active region of Kazakhstan (Sokolova et al., 2017).

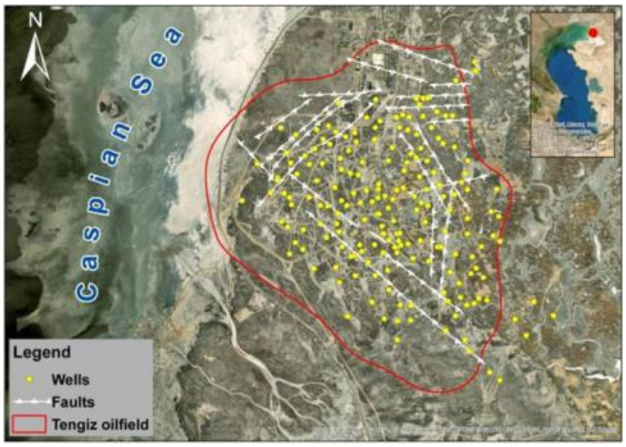

Figure1. Tengiz oilfield with the representation of wells.

2.2. Quantitative Assessment of Ground Deformations at Tengiz Oilfield using SBAS Techniques, 3D & 2D Decompositions and Cosine Corrections

C-band (5.6 cm wavelength and 5.4 GHz) Sentinel-1 A/B TOPS images from the European Space Agency (ESA) were used for the present research to map the spatial distribution and rates of ground deformation at the Tengiz oilfield. Sentinel-1 VV polarization bands were used since co-polarized bands provide higher coherence (Imamoglu et al., 2019). As it is possible to observer in Figure 2a, the study area was fully covered by all three tracks. Sentinel-1 images in wide-swath mode provide a wide coverage of about 250 km with a slant range resolution of 5 m and an azimuth resolution of 20 m (Yang et al., 2019). The connection graphs of SAR images in Figure 2b and Figure 2c show that all radar images were well connected in time in order to follow the displacement monitoring over the period of 2018-2020. The interferometric processing was performed using the Small Baseline Subset (SBAS) technique followed by 3D and 2D decompositions, cosine corrections and geospatial analysis to derive both vertical and horizontal deformations (Figure 3).

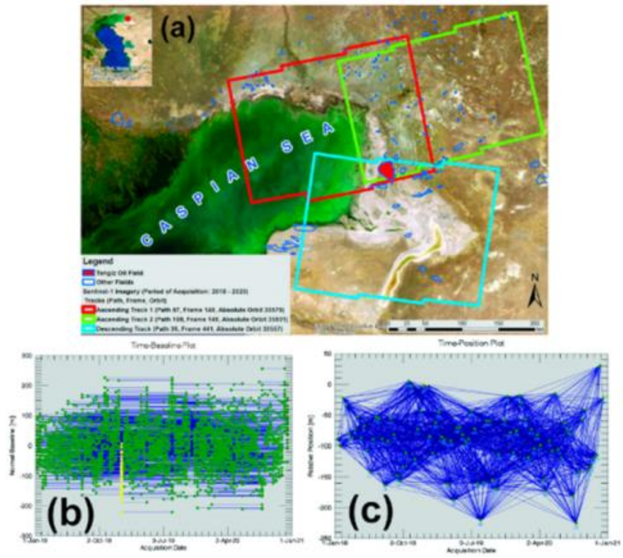

Figure 2. (a) Sentinel-1 imagery track numbers and acquisition details; connection graphs: (b) time-position plot for SBAS; (c) time-baseline plot for SBAS.

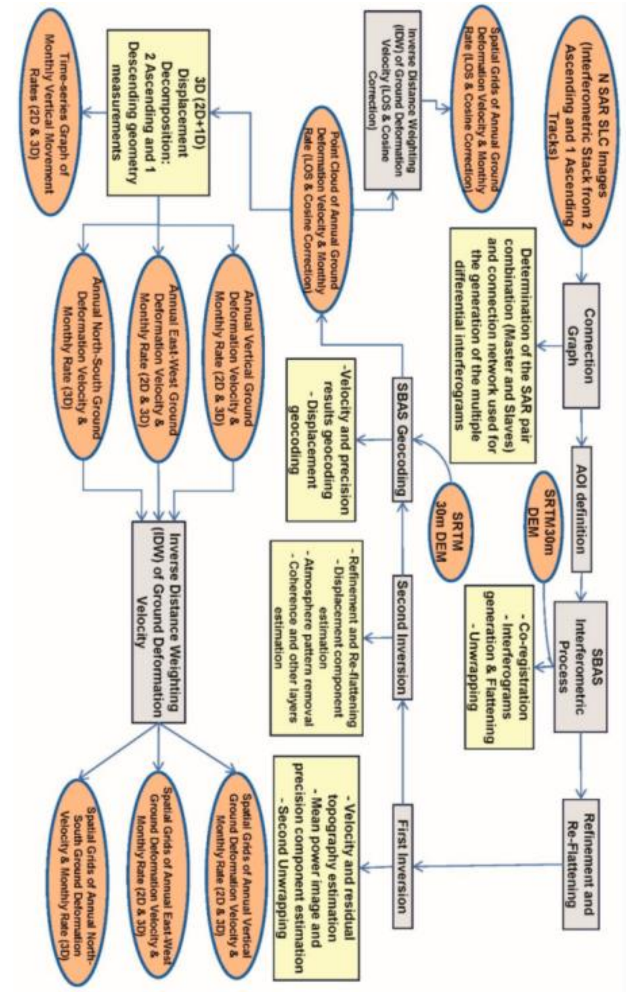

Figure 3. Workflow of SBAS interferometric processing followed by 2D and 3D decompositions, cosine correction and geostatistical interpolations.

3. Results

The 3D and 2D decompositions of LOS measurements 2018-2020 to vertical displacement allowed to determine that annual average vertical deformation velocity over the Tengiz oilfield was in the range of – 70.04-22.44 mm/year and –73.29-23.70 mm/year, respectively (Figure 4a, b).

The range of vertical subsidence velocities was observed to be slightly higher than in case of LOS measurements. Based on the Pearson Correlation Coefficient > 90 and t-test p-value > 0.05 in Figure 4c and Figure 4d, it is possible to conclude that both 3D and 2D decompositions produced identical vertical deformation velocities with an RMSE of 1.86 mm. Even though many research activities applied the LOS measurements for the operational purposes of oil and gas fields, as mentioned before, it was possible to observe differences in LOS displacements compared to 3D and 2D decomposition results (Figure 4d).

The vertical velocity obtained through the division of the LOS displacement rates by the cosine of the radar incidence angle is presented in Figure 5a-c. The histogram of vertical velocity distribution derived from cosine correction is presented in Figure 5d. Like the previously mentioned histogram of LOS measurements, in this case it was also possible to observe significant variations in the spatial distribution of ground deformation values (Figure 5d). These variations might also create a challenge and uncertainties for the oil and gas operators even though the cosine correction was applied to derive vertical deformation velocity. However, the RMSE between vertical deformation velocities derived from cosine correction and from 3D decomposition reduced twice with the variation in the range of 6-8 millimetres. Along the profiles in Figure 5a-c it was possible to observe differences between 3D decomposition vertical deformation and cosine-corrected velocities in the range of 0-17 mm (Figure 5e). It is possible to conclude that the cosine correction of LOS measurements to vertical deformation velocity obviously improved the overall reliability of ground movement measurements. However, it is still possible to observe variations along the profile which may also create a different kind of uncertainties for the operators of oil and gas fields.

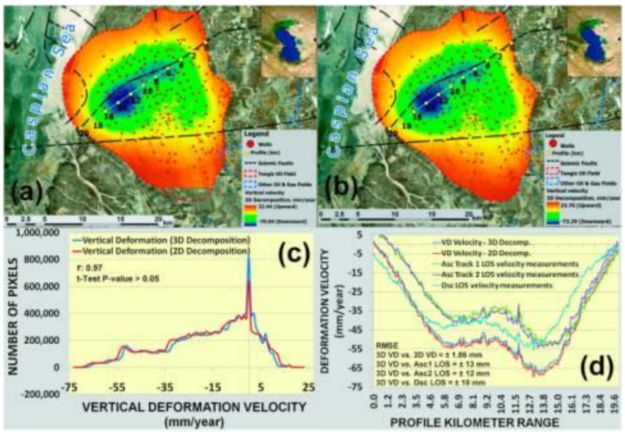

Figure 4. Vertical deformation velocity derived: (a) from 3D decomposition of 2 ascending and 1 descending LOS measurements; (b) from 2D decomposition of 1 ascending and 1 descending LOS measurements; (c) histogram of vertical deformation velocities derived from 3D and 2D decompositions; (d) profiles of vertical deformation velocities derived from 3D and 2D decompositions and LOS measurements.

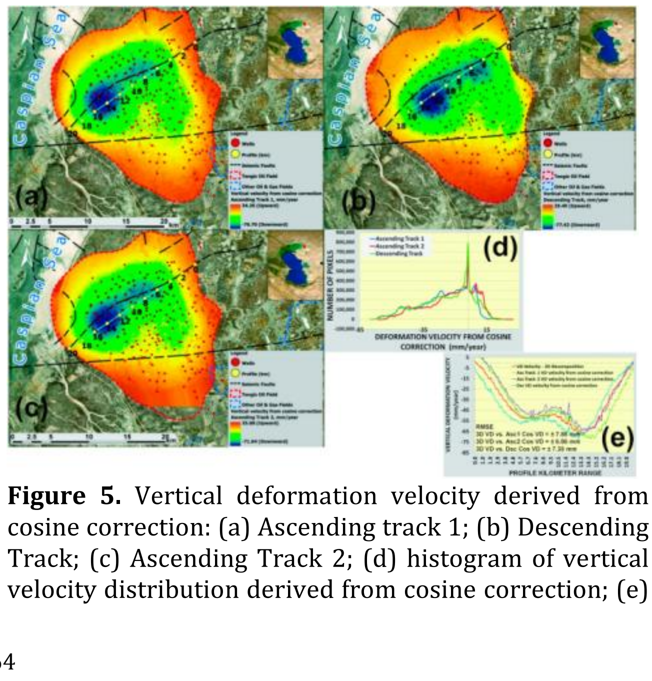

Figure 5. Vertical deformation velocity derived from cosine correction: (a) Ascending track 1; (b) Descending Track; (c) Ascending Track 2; (d) histogram of vertical velocity distribution derived from cosine correction; (e)

comparison of vertical velocity profiles derived from 3D decompositions and cosine corrections.

The hotspot of significant subsidence is located at the intersection of profile lines in Figure 6a and Figure 6b. The location of maximum subsidence velocity was also observed at the intersection of profiles indicated in Figure 6a. As it is possible to see in Figure 6b, the maximum annual vertical deformation velocity of maximum subsidence along profiles reaches about 70 mm. Location and time series of cumulative ground displacement rates of the maximum subsiding position are presented in Figure 6c and Figure 6d, respectively, for LOS measurements and their 2D and 3D decompositions to vertical movements. The ground deformation rate at the maximum subsiding location reaches about 200 mm of vertical ground movement derived from 3D decomposition of LOS measurements over the period of 2018-2020 (Figure 6c; Figure 6d). The differences of vertical deformation rates derived from 3D decomposition and cosine corrections at the maximum subsiding site vary in the range of 0-50 mm (Figure 6d). RMSE between vertical deformation rates from 3D and 2D decompositions and cosine correction was observed to be in the range of 30-40 mm (Figure 6d).

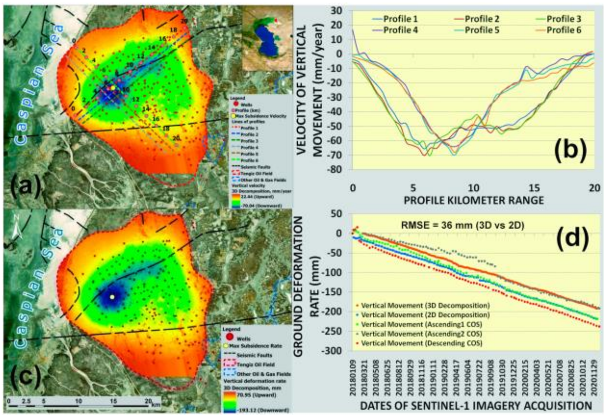

Figure 6. (a) Location of maximum subsidence in the area of vertical deformation velocity derived from 3D decomposition; (b) Profiles of vertical movement velocity; (c) Maximum subsiding location with the background of vertical deformation rate derived from 3D decomposition; (d) Vertical deformation rates derived from 3D and 2D decompositions and cosine corrections for the location of maximum subsidence.

The 3D and 2D decomposition of LOS measurements 2018-2020 to horizontal east-west displacement allowed to determine that annual average horizontal deformation velocity over the Tengiz oilfield was in the range of –25.48-21.33 mm/year and –23.17-22.82 mm/year, respectively (Figure 7a; Figure 7b). Although the annual average horizontal deformation velocity was not significant, it was interesting to find both eastward and westward horizontal movements. Based on the Pearson Correlation Coefficient > 80 and a t-test p-value > 0.05 in Figure 7c and Figure 7d, it is possible to conclude that both 3D and 2D decompositions produced identical horizontal deformation velocities with an RMSE of 1.62 mm. This allows to state that 2D decomposition of LOS measurements will be sufficient for the future deformation analysis by oil and gas operators of the Tengiz oilfield.

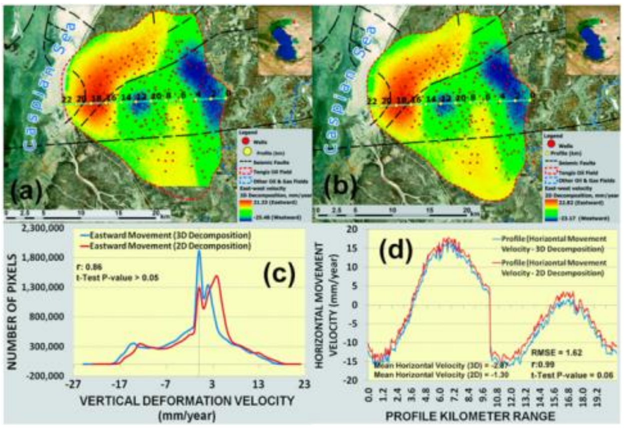

Figure 7. East-west movement velocity derived from: (a) 3D decomposition of 2 ascending and 1 descending LOS measurements; (b) 2D decomposition of 1 ascending and 1 descending LOS measurements; (c) histogram of east-west movement velocities derived from 3D and 2D decompositions; (d) profiles of east-west movement velocities derived from 3D and 2D decompositions.

The 3D decomposition of LOS measurements 2018 -2020 to horizontal north-south displacement allowed to determine an annual velocity over the Tengiz oilfield in the range of –5.54-8.12 mm/year (Figure 8a). Even though the north-south movement was not significant, the interesting pattern of the Tengiz oilfield northern area moving southward and southern area moving northward towards seismic fault was observed (Figure 8b). This, in return, allowed to assume that this area is under the impact of natural, i.e., not man-made, tectonic processes as it was also determined by Anissimov et al. (2020). This fact may increase the negative impacts on the Tengiz oilfield through the acceleration of the subsidence processes caused by the man-made oil extraction processes. The spatial relationships between the seismic faults and horizontal and vertical movements were well reflected in the 3D representation of the ground deformation velocities (Figure 9a–d).

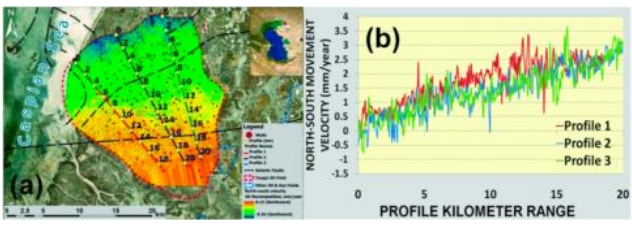

Figure 8. (a) North-south movement velocity derived from 3D decomposition of 2 ascending and 1 descending LOS measurements; (b) North-south movement velocity along profiles

Unfortunately, because of the absence of historical cumulative high-precision GPS measurements, it was not possible to validate the SBAS measurements, the results of 2D and 3D decompositions and cosine corrections. The only possible qualitative judgment was conducted based on the studies by Grebby et al. (2019)

which also revealed a continuous subsidence at the Tengiz oilfield.

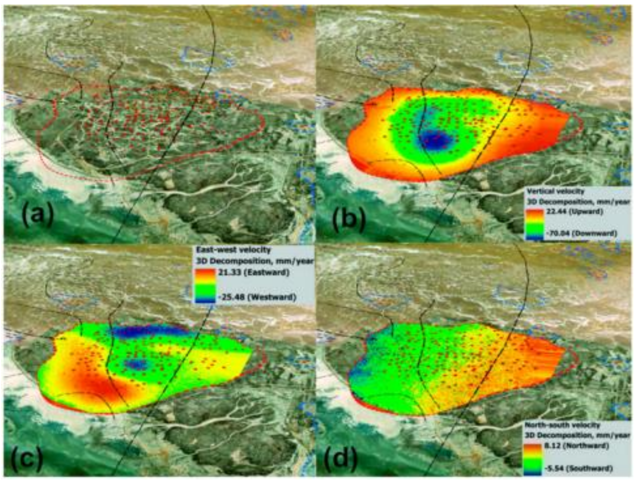

Figure ***9.*** Oblique aerial view of: (a) Tengiz oilfield; (b) vertical deformation velocity derived from 3D decomposition; (c) east-west movement velocity derived from 3D decomposition; (d) north-west movement velocity from derived from 3D decomposition.

4. Discussion

Based on the results of the present research, it was possible to conclude that the subsidence processes in the Tengiz field continue with increasing velocity. 3D and 2D decompositions of LOS measurements concerning vertical deformation revealed twice lower differences in comparison to cosine correction than with LOS measurements. The role of 3D and 2D decompositions to vertical velocities becomes even more indicative in this case, if sufficient number of SAR data is available from ascending and descending tracks. Even though the vertical deformation confirmed typical patterns of subsidence caused by oil extraction, detected east-west and north-south movements at the Tengiz oilfield clearly indicated that the study area crossed by seismic faults is affected by natural tectonic processes. It is necessary to emphasize that the spatial patterns of east-west and north-south ground movements were observed to both sides of the seismic faults. A seismic fault was also observed crossing the detected hotspot of subsidence. This means that the natural tectonic processes at the Tengiz oilfield should also be considered as one of the significant risk factors which might have significant consequences like induced seismicity and infrastructure failure as a result of ongoing oil field exploitation.

The outcomes of the present research suggest to the operators of oil and gas fields to initially evaluate required standards and precision of measurements depending on the operational needs. In particular oil and gas operators should be aware that even though LOS measurements present the overall ground movement patterns, they do not reflect true vertical movement values at the local scale. Therefore, planning of actual risk mitigation and remediation measures on the ground might be misleading unless LOS measurements are decomposed to vertical deformation velocities and rates.

5. Conclusion

The present research investigated the surface deformations induced by man-made production and natural processes in the Tengiz oilfield using SBAS technique and 3D and 2D decompositions of LOS measurements to vertical and horizontal deformations. Our conclusions and recommendations are as follows:

(1) 3D decomposition of LOS measurements concerning vertical movements showed that the Tengiz oilfield continued to subside during 2018-2020 with a maximum annual vertical deformation velocity around 70 mm. Following LOS measurements, the maximum annual subsiding velocity was observed to be 60 mm. Cosine corrections of LOS measurements to vertical movement revealed a maximum annual vertical deformation velocity of 77 mm.
(2) Overall RMSE between 3D decomposed vertical deformation and LOS measurements was observed to be in the range of 10-13 mm. The differences on the local level were variable in the range of 7-21 mm.
(3) Overall RMSE between 3D decomposed and cosine-corrected vertical deformations was observed to be in the range of 6-8 mm. Compared to LOS measurements, the cosine-correction improved the results of vertical deformation twice relative to 3D and 2D decomposition. The differences on the local level were variable in the range of 0-17 mm.
(4) The ground deformation rate at the location of maximum subsidence reached around 200 mm of vertical ground movement derived from 3D decomposition of LOS measurements over the period of 2018–2020. The differences of vertical deformation rates derived from 3D decomposition and cosine corrections at the site of the maximum subsidence varied in the range of 0-50 mm. RMSE between vertical deformation rates from 3D and 2D decompositions and cosine correction was observed to be in the range of 30-40 mm. Besides the ground deformation velocity, it is highly important to consider the total displacement reflected in the deformation rate of individual sites of interest.
(5) The vertical deformation confirmed typical patterns of subsidence caused by oil extraction. Detected east-west and north-south movements at the Tengiz oilfield clearly indicated that the study area crossed by seismic faults is affected by natural tectonic processes. It has to be emphasized that the spatial patterns of east-west and north-south ground movements were observed on both sides of seismic fault crossing the detected hotspot of subsidence. It is possible to conclude that the natural tectonic process at the Tengiz field is one of the significant risk factors which might have significant consequences like induced seismicity and infrastructure failure as a result of ongoing man-made oil field exploitation. It is critical for operators of oil and gas fields and also other types of oil and gas infrastructure to realize the actual differences of ground deformation measurements derived from 3D and 2D decompositions,

cosine correction and LOS measurements. This will allow to initially evaluate the required standard and precision of measurements depending on operational needs, timeframes and availability of imagery. Since it was not possible to validate the results of the present research, it is planned to use higher resolution SAR sensors to cross-validate the achieved results.

Acknowledgement

This research was funded by the Nazarbayev University through the Social Policy Grant (SPG) and Faculty-development Competitive Research Grant (FDCRGP) - Funder Project Reference: 080420FD1917.

References

Anissimov, L., Postnova, E., & Merkulov, O. (2000). Tengiz oilfield: geological model based on hydrodynamic data. Petroleum Geoscience, 6(1), 59-65.

Bayramov, E., Buchroithner, M., & Kada, M. (2020a). Quantitative assessment of ground deformations for the risk management of petroleum and gas pipelines using radar interferometry. Geomatics, Natural Hazards and Risk, 11(1), 2540-2568.

Bayramov, E., Buchroithner, M., & Kada, M. (2020b). Radar remote sensing to supplement pipeline surveillance programs through measurements of surface deformations and identification of geohazard risks. Remote Sensing, 12(23), 3934.

Bayramov, E., Buchroithner, M., Kada, M., Bayramov, R. (2020c). Quantitative assessment of ground deformation risks, controlling factors and movement trends for onshore petroleum and gas industry using satellite Radar remote sensing and spatial statistics. In Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards; Taylor & Francis: London, UK.

Bealessio, B. A., Blánquez Alonso, N. A., Mendes, N. J., Sande, A. V., Hascakir, B. (2020). A review of enhanced oil recovery (EOR) methods applied in Kazakhstan. Petroleum, 7, 1–9.

Grebby, S., Orynbassarova, E., Sowter, A., Gee, D., & Athab, A. (2019). Delineating ground deformation over the Tengiz oil field, Kazakhstan, using the Intermittent SBAS (ISBAS) DInSAR algorithm. International Journal of Applied Earth Observation and Geoinformation, 81, 37-46.

Imamoglu, M., Kahraman, F., Cakir, Z., & 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(9), 1069.

Klein, I., Gessner, U., & Kuenzer, C. (2012). Regional land cover mapping and change detection in Central Asia using MODIS time-series. Applied Geography, 35(1-2), 219-234.

Mirzaii, Z., Hasanlou, M., Samieie-Esfahany, S., Rojhani, M., & Ajourlou, P. (2019). Land subsidence monitoring in azar oil field based on time series analysis. Multidisciplinary Digital Publishing Institute Proceedings, 18(1), 2.

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. Ph.D. Thesis, Satbayev University, Almaty, Kazakhstan.

Shi, J., Yang, H., Peng, J., Wu, L., Xu, B., Liu, Y., Zhao, B. (2019). InSAR Monitoring and analysis of ground deformation due to fluid or gas injection in Fengcheng oil field, Xinjiang, China. J. Indian Soc. Remote Sensing, 47, 455–466.

Sokolova, I. N., Mikhailova, N. N., Velikanov, A. E., Poleshko, N. N. (2017). Induced seismicity on the territoryof Kazakhstan. In Book of Abstracts CTBT: Scienceand Technology Conference; CTBTO: Vienna, Austria.

Yang, C., Zhang, D., Zhao, C., Han, B., Sun, R., Du, J., Chen, L. (2019). Ground Deformation Revealed by Sentinel-1 MSBAS-InSAR Time-Series over Karamay Oil field, China. Remote Sensing, 11, 2027.