Analysis of Crustal Movements in the Angren-Almalyk Mining Industrial Area Using GNSS Data

Fazilova, D.,[1, 2, 3*] Makhmudov, M.[2,3] and Magdiev, K. H.[1,4]
[1]Space Researches laboratory, Astronomical Institute of Uzbek Academy of Sciences, Republic of Uzbekistan
E-mail: dilfaz@yahoo.com*
[2]Geodesy and Geoinformatics Department, National University of Uzbekistan named after Mirzo Ulugbek, Republic of Uzbekistan
[3]Mine Surveying and Geodesy Department, Tashkent state technical university named after Islam Karimov, Republic of Uzbekistan
[4]Project Implementation Unit, Cadaster agency under Economy and Financial Ministry of Republic Uzbekistan
E-mail: hasan.magdiev@gmail.com
*Corresponding Author

DOI: https://doi.org/10.52939/ijg.v19i11.2915

Abstract

This study aims to investigate the potential of GNSS data in earthquake zoning and risk assessment in a seismically active region. The study area is located in Uzbekistan, where the interaction of several tectonic plates results in frequent earthquakes. The study focused on two periods from October to October of the next year, respectively, for 2018 and 2019, 2019 and 2020 to analyze GNSS velocities and earthquake zoning maps to identify areas at high risk of seismic activity. The study also utilized GIS and spline interpolation to create continuous surface maps of risk zones based on earthquake hazard data. The results showed that the entire study area is at high seismic risk, with a tendency for rotational movement in the zone of intersection of tectonic plates. Velocities range from 1.56-20.3 mm/yr and 1.64-14 mm/yr for the two periods. Moreover, the analysis of vertical earth surface displacements indicates a tendency towards soil subsidence in the western part and uplift in the northeastern part of the study area. The study concludes that GNSS analysis can provide valuable insights into seismic hazard assessment and improve our understanding of the tectonic processes leading to earthquakes.

Keywords: Deformation, Earthquake, GNSS, Risk Zone, Velocities

1. Introduction

The Angren-Almalyk mining area is one of the most famous and developed industrial regions of Uzbekistan, characterized by a high concentration of enterprises in coal mining, mining industries, construction, electric power, industrial and civil engineering facilities, and irrigation systems. The area includes the Angren coalmine up to 300 meters deep, the Dzhigiristan quarry, the Naugarzan and Apartak coal quarries, and the Almalyk Mining and Metallurgical Complex, which is the base production of non-ferrous metals in Uzbekistan. The industrial center is the city of Almalyk, located 50 km southeast of the capital Tashkent. The territory is confined to a zone of intense tectonic activity, which is also enhanced by increased watering of the territory. According to the peak ground acceleration map, it belongs to one of the two fields in the country of very high seismic activity up to 4.8 m/s^2 [1]. The magnitude of the maximum ground velocity must exceed values for 50 years 50 cm/s with probability $P = 0.99$, according to the analysis of the velocity graphs of M3.8–6.2 earthquakes [2]. Most of the Tashkent region is in a state of high compressive strain (negative dilatation) [3]. Cataclastic analysis of displacements along fault sets confirmed a near-latitudinal direction of the main stress axis of maximum compression in the territory [4]. Early studies of the Tashkent geodynamic polygon, located in the northern part of the region, have identified the technogenic factor as another contributor to disturbances in the earth's surface, specifically changes in the water level of the Charvak reservoir.

Further investigations into the stress state and its relationship with earthquakes of magnitude greater than 3 have revealed that approximately 20 days prior to the earthquakes, there was an observed increase in the stress state, followed by a decrease approximately 16 days after the event [5]. Overall, these findings highlight the need for careful monitoring and management of deformation processes in this region to minimize the risk of seismic events and other potential hazards.

The widespread use of space geodetic methods has had a significant impact on Earth's surface deformations. In particular, networks of permanent GNSS stations make it possible to calculate station velocities with high precision and contribute to the monitoring of deformation processes. According to [6] [7] and [8], recent studies have demonstrated significant advantages of geodetic surveys in the field of deformation control, specifically in mining areas. In this paper, we present the results of earth surface deformations in the Angren-Almalyk mining region using GNSS measurements for the 2018-2020 period.

2. GNSS Data and Processing

GNSS measurements were begun in 2005 in Uzbekistan. The State Geodetic Network (SGN) was developed in several stages by Agency for cadaster of the Republic of Uzbekistan. The site selection aimed to cover geographically all densely populated eastern parts of the country’s territory. To date, it includes about 200 stations of several subnetworks: Reference Geodetic Points (RGP), Satellite geodetic network 0th class points (SGN-0), and Satellite geodetic network first-class points (SGN-1). The periods of station installation and the number of points of various subnets were described in detail in the previous work of the authors [9]. Since 2018, 50 of them have been transferred to the mode of continuously operating reference station.

The considered in this work network consists of 10 stations (ALMA, ANGR, BUKD, CHIR, GAZA, MADK, MTAL, TASH, TOYT) in the Angren-Almalyk mining region and the surrounding areas (Figure 1). Depending on data availability, we selected 6 measurement campaigns for analysis. The duration of each varies from one to four months (Table 1). Two periods from October to October of the next year, respectively, for 2018 and 2019, 2019 and 2020 were selected for studying deformations of the region. The GAMIT/GLOBK v.10.71 software package was used for GNSS phase observations processing for estimating the position and velocity of stations [10].

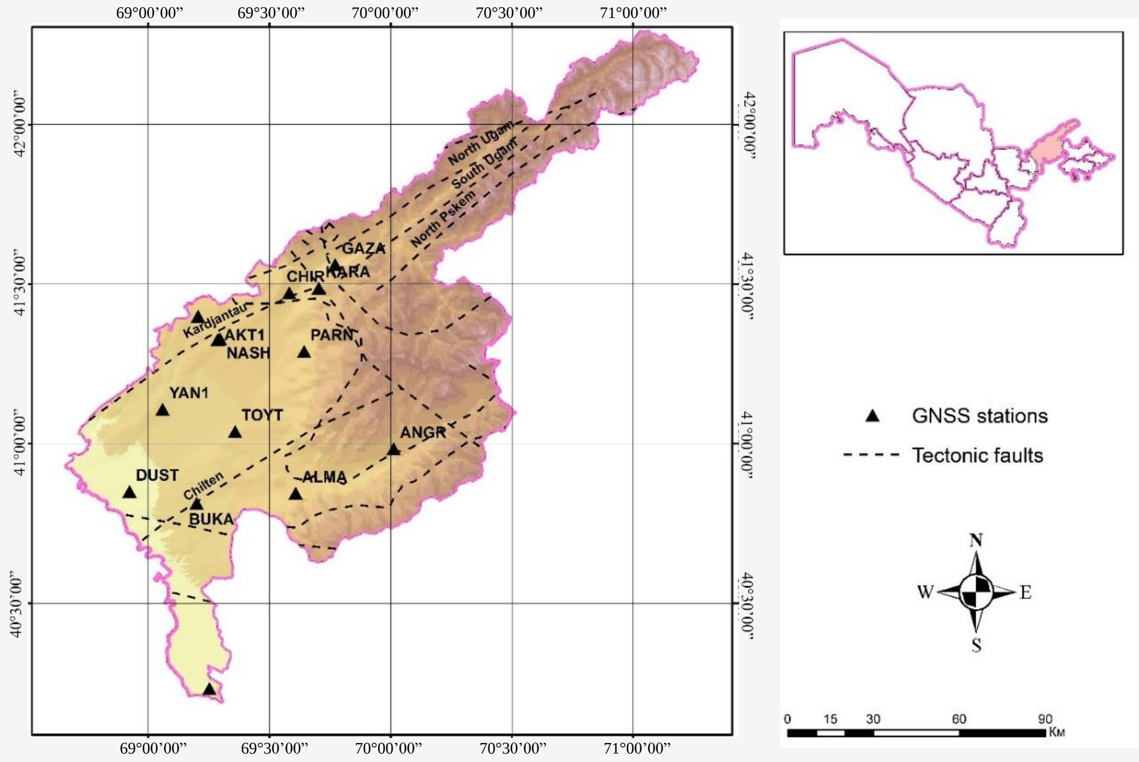

Figure 1: GNSS network distribution in the study area

Table 1: Periods (days of the month) of the selected observations stations in this study

Year/Month	January	February	March	April	July	August	September	October
2018	-	-		-	-	-	-	1-26
2019	10-31	1-28	1-31	1-30	-	-	29-30	1-26
2020	1-31	-	-	1-30	1-31	1-31	1-30	1-31

The processing includes 3 stages [11]. In the first stage, daily phase measurements were used to estimate the coordinates of the stations and the zenith delay of the atmosphere at each station, as well as the parameters of the satellite orbits and the orientation of the Earth. Automatic iteration in the GAMIT block, using the least squares method, is performed until the remaining values of the a-priori-specified and estimated coordinates are obtained down to the millimeter level. At the same time, in the autcln program, cyclic shifts are restored or removed using double or triple differences of observations. For all solutions, high-precision IGS (International GNSS Service) satellite orbits were used. For each of the satellites, the ambiguity of 95% was estimated using a combination of Melbourne-Wubben [12] and satellite delay code offset data. In addition, standard models were selected for analysis: the IERS-1992 gravitational field [13], the model of non-gravitational accelerations of satellites [14], the GPT2 global pressure and temperature model [15] for zenith delay correction, Saastamoinen's model for estimating the dry and wet parts of atmospheric delays [16], and the FES2004 ocean tidal load model [17]. To connect the regional network with the global reference system ITRF2014, 12 continuously operating International GNSS service (IGS) stations (ARTU, BADG, CHUM, GUAO, HYDE, IISC, KAZA KIT3, POL2, SHAO, TASH, URUM) were included in the processing. In the second stage, daily files were combined into free limited solutions for each session of the regional campaign. And, finally, at the third stage, individual solutions obtained using the Kalman filter in the GLOBK module [18] were used to estimate a consistent set of coordinates and velocities of points in the ITRF2014 International Terrestrial Reference System [19].

The reference frame implementation is applied using a set of globally distributed constraint stations and a solution for offset, rotation, and scale factors. The quality of the initial data was assessed by the values of standard deviations for each satellite and station. The error range for the best stations was from 4.0 mm to 5.3 mm, and for the worst stations, from 8.0 mm to 12.4 mm. An error level of more than 10 mm is high, but acceptable, according to the software developers, and may be due to external sources of noise (for example, poor observation quality, signal multipath) according to the software developers [10]. The ambiguity resolution percentage was 97% for Wide Lane and 91% for Narrow Lane lanes. This confirms the good quality of the initial data for obtaining a reliable solution, the absence of noisy pseudoranges, good network size and configuration, session duration, quality of orbits and a priori coordinates, and atmospheric conditions. The normalized root-mean-square value for solutions with constraints without ambiguities, with constraints with disambiguated, free without ambiguities, and free with resolved ambiguities was about 0.19 mm for all observation sessions.

The determination of the reference frame and connection to the global reference frame was carried out using daily combined solutions by stabilization using a priori given velocities in ITRF2014. For local deformation interpretation, we express velocities relative to the Eurasia “fixed” plate. It was realized by estimating seven parameters (three velocity components, scale, and three rotation parameters) relative to the global frame by minimizing the horizontal velocities of stable sites of international IGS stations relative to the ITRF2014 system using the angular velocity of rotation of the Eurasian plate according to [19]. To obtain the velocity field for the region, the "Spline" interpolation method was used in the ArcGIS software.

3. Results and Discussion

GNSS data provides a valuable tool for measuring crustal deformation and understanding the tectonic processes that lead to earthquakes. By analyzing GNSS velocities in conjunction with an earthquake zoning map, we can identify areas that are experiencing high rates of strain accumulation, which can indicate a higher potential for seismic activity. This information can be used to refine the earthquake zoning map and improve our understanding of seismic risk in the region.

Furthermore, comparing the earthquake zoning map with GNSS velocities can provide insights into the relationship between seismic hazard and surface deformation. By analyzing how these two factors are correlated, we can better understand the factors that control seismic activity and potentially identify areas that may be at increased risk of earthquakes in the future.

Therefore, at this stage of the analysis, we built the map of risk zones. The capabilities of geographical information system (GIS) are valuable for geospatial modelling of earthquake data by utilizing spatial statistical analysis tools. Spline interpolation is a mathematical technique that allows the creation of a continuous surface from a set of scattered points. This approach is useful when dealing with point data that is unevenly distributed across a study area and requires an estimate of the hazard distribution over the entire area. Spline interpolation is a mathematical technique that involves fitting a smooth curve to a set of data points by minimizing the overall curvature of the curve. Several studies have utilized the Spline interpolation method in earthquake hazard mapping, as documented in [20] [21] and [22]. The catalog of the republican seismological center was used for the analysis [23]. Because an earthquake M < 2.0 is very weak, occurs many times a day and people do not feel it, we only considered M>3. Figure 2 shows the resulting earthquakes zoning maps for two considered periods.

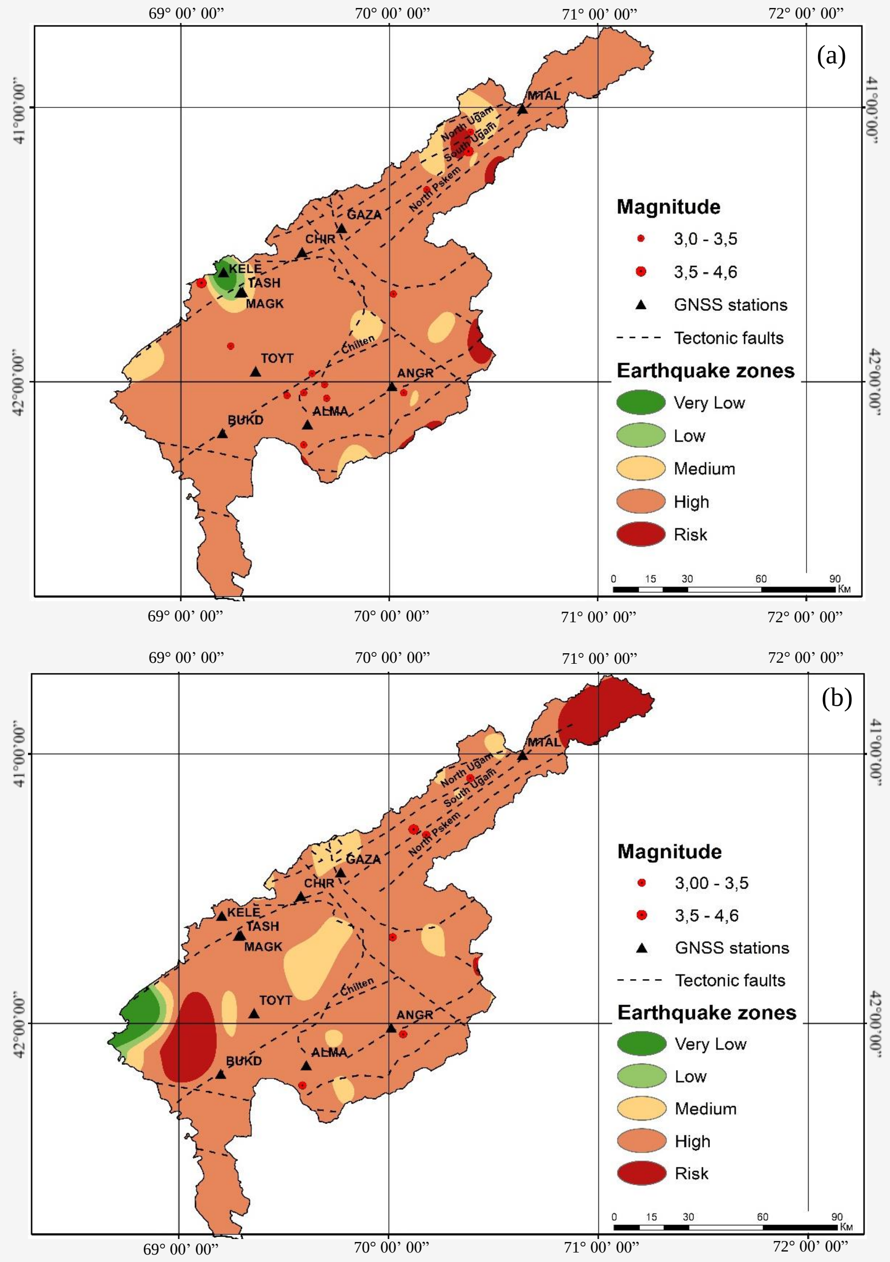

Figure 2: The earthquakes zoning maps (a) 2018-2019 and (b) 2019-2020

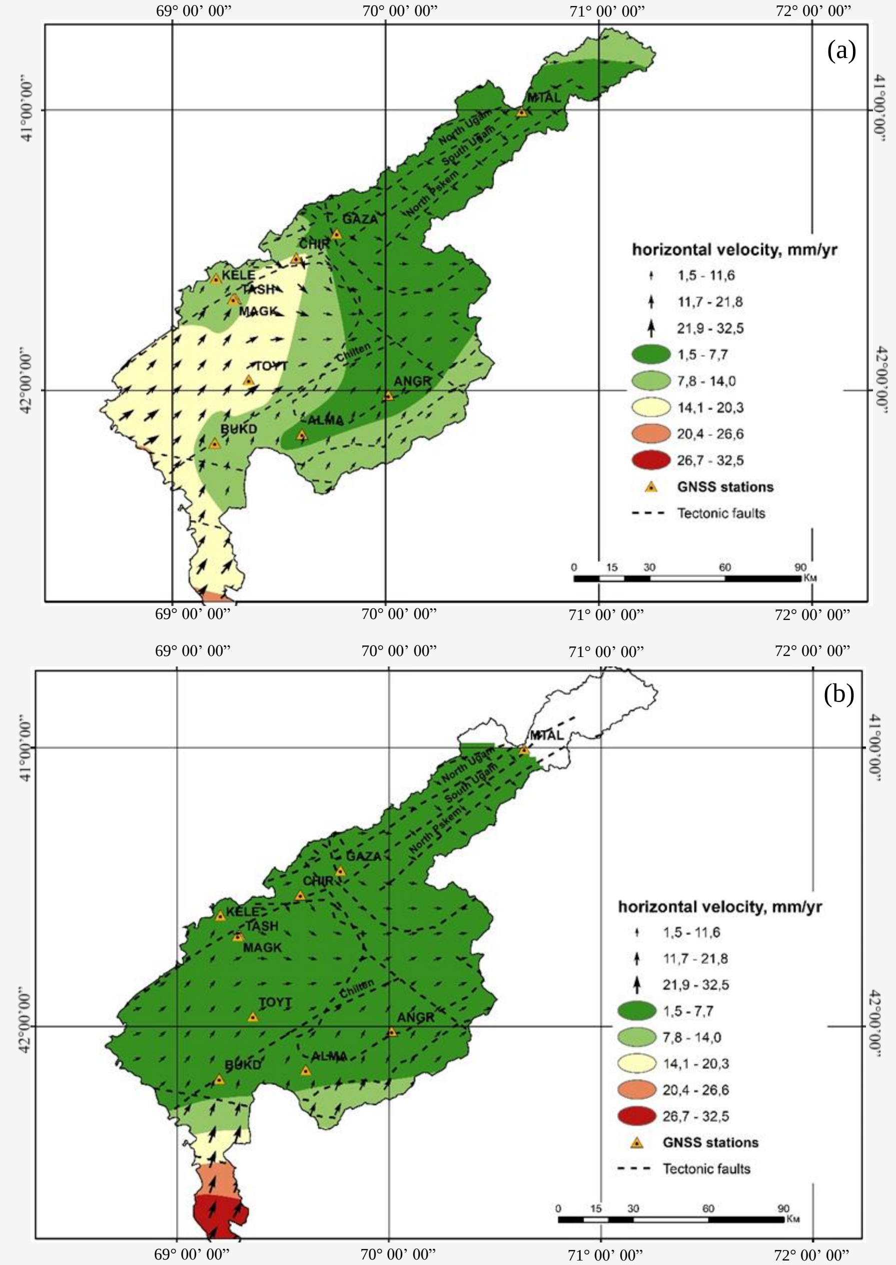

Figure 3: The computed annual horizontal GNSS velocities relative to Eurasian “fixed” frame (a) 2018-2019 and (b) 2019-2020

At the same time, it should be noted that the entire study area belongs to the zone of high seismic risk. The outlook of regional seismicity manifests that the seismicity is well correlated over the mosaic of lithospheric plates in study area. At the same time, during 2019-2020, the territory east of the industrial centers of Angren and Almalyk and the northern mountainous part of the region was marked as a risk zone.

The station's horizontal velocity vectors and the consistent velocity field relative to “fixed” Eurasia for both considered periods are shown in Figure 3. The station's velocities are ranging from 1.56 mm/yr to 20.3 mm/y for the first period of observation (from October 2018 to October 2019) (Figuge 3(a)). In the zone of intersection of tectonic plates Karjantausky, Kumbelsky, and Chatkalsky, a tendency to rotational movement is visible.

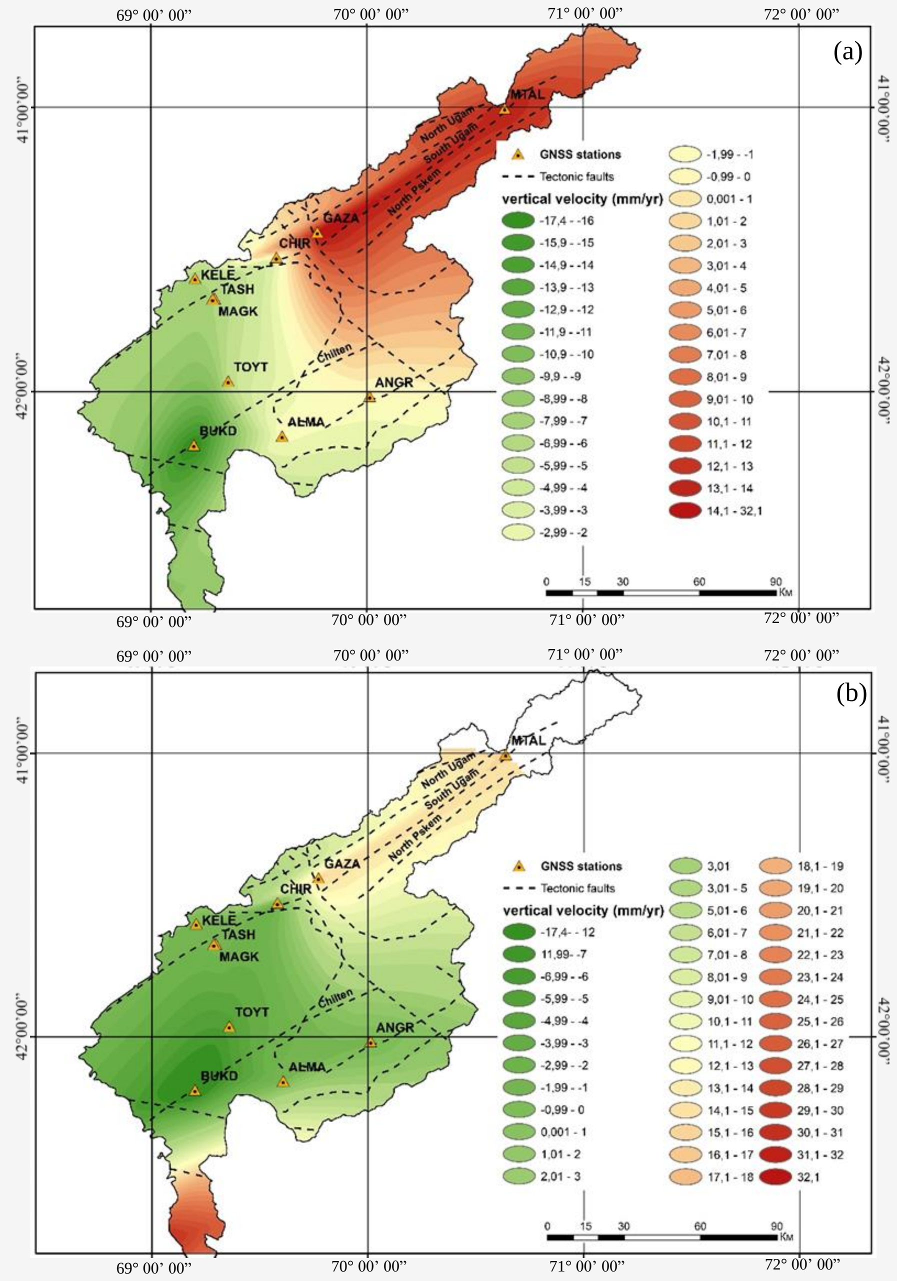

Figure 4: The computed annual vertical GNSS velocities (a) 2018-2019 and (b) 2019-2020

The velocity field shows extremal values in the eastern mountain part of the region. Undoubtely, GNSS velocities are an implication of the tectonic activity of the region. Nevertheless, we can also observe a large number of earthquakes in this area during this period (Figure 2(a)), which could also be the result of an increase in velocity. In the southeastern part of the zone near the city of Almalyk, the average rate in the first period was about 14 mm/year. It is in this part of the territory that most of the seismic events that occurred during this period are concentrated. According to the results, the values of velocities range from 1.64 mm/yr to14 mm/yr for the second period. There is a tendency for the rate to decrease to 7 mm/year. However, as we mentioned earlier, this area was still at risk during the second period (Figure 3(b)). Figure 4 shows the vertical earth surface displacements in the region.

We have obtained two regions with different vertical movements. For the first, western part of the territory, there is a tendency for soil subsidence of up to 17 mm/year during both observation periods. This is likely influenced by mining activities near the cities of Angren and Almalyk. The northeastern part of the territory is of particular interest, as there is a tendency towards uplift instead. The high dynamics of vertical movements can be traced in mountainous areas in the northeastern part of the study area, which was obtained as a zone of maximal seismic risk. Vertical movements in the northeastern part of the territory may be associated with tectonic, erosional and seismic activity, as well as changes in the water regime, such as glacier melting, which could lead to a change in the loading, and, as a result, to vertical deformations. At the same time, we observe subsidence of the Earth surface in the industrial southwestern part of the region.

4. Conclusion

The observed horizontal and vertical movements of the earth's crust in the Angren-Almalyk industrial zone are important for understanding the geological processes that take place in the region. The tectonic activity of the region is the primary cause of the observed horizontal movements, which are reflected in the rates of GNSS stations. The rotational movement detected in the zone of intersection of the Karzhantau, Kumbel, and Chatkal tectonic plates is a notable feature of this area, which can lead to significant deformation of the earth's crust. Moreover, the observed extreme values in the velocity field of the western part of the region are of particular interest because they are caused by mining operations. Such anthropogenic activity can significantly affect the dynamics of the earth's crust, leading to surface deformation and ground instability. This effect is of concern, given that the study area is located in a zone of increased seismic risk, where the occurrence of earthquakes and other geological hazards is common.

Therefore, understanding the relationship between mining operations and the earth's crust dynamics is crucial for developing effective strategies to mitigate potential risks. The observed vertical movements of the earth's surface in the study area are also noteworthy. The subsidence of the earth's surface in most areas to 17 mm/year and the tendency for significant vertical displacements in the northern part of the region are likely due to tectonic factors and changes in the water regime. In mountainous regions, changes in the water regime can cause significant deformation of the earth's crust, affecting slope stability and potentially leading to landslides and other hazards. In conclusion, the observations and analyses presented in this paper highlight the complexity of the geological processes that take place in the Angren-Almalyk industrial zone. Understanding the underlying factors that drive the observed horizontal and vertical movements of the Earth's crust is critical for assessing and mitigating potential geological hazards in the region. Further studies with a denser local network of observations could provide a more accurate assessment of the physical nature of the earthquakes and displacements in this area. This, in turn, could inform more effective strategies for mitigating risks and protecting local communities and infrastructure

Acknowledgements

This work was carried out within the scientific project of the Astronomical Institute of Uzbekistan with the financial support of the Academy of Sciences of the Republic of Uzbekistan. We are very grateful to the Agency for Cadaster, who organized GNSS experiments and made the data available for this study. GNSS data were processed using the GAMIT/GLOBK software. We would also like to thank reviewers for their many constructive comments and suggestions.

References

[1] Giardini, D., Gruenthal, G., Shedlock, K.M. and Zhang, P., (2003). 74 - The GSHAP Global Seismic Hazard Map. *International Geophysics*, Vol. 81, 1233-1239. https://doi.org/10.1016/S0074-6142(03)80188-2.

[2] Artikov, T. U., Ibragimov, R. S., Ibragimova, T. L., Kuchkarov, K. I. and Mirzaev, M. A., (2018). Quantitative Assessment of Seismic Hazard for the Territory of Uzbekistan According to the Estimated Maximum Ground Oscillation Rates and their Spectral Amplitudes. *Geodynamics & Tectonophysics*, Vol. 9, No. 4, 1173–1188. https://doi.org/10.5800/GT-2018-9-4-0389.

[3] Fazilova, D. and Sichugova, L., (2021). Deformation Analysis based on GNSS Measurements in Tashkent Region. *E3S Web Conf.*, Vol. 227. https://doi.org/10.1051/e3sconf/202122704002.

[4] Rebetsky, Y. L., Ibragimova, T. L., Ibragimov, R. S. and Mirzaev, M. A., (2020). Stress State of Uzbekistan’s Seismoactive Areas. *Voprosy Inzhenernoi Seismologii (Problems of Engineering Seismology)*, Vol. 47, No. 3, 28–52. https://doi.org/10.21455/VIS2020.3-2.

[5] Sichugova, L. and Fazilova, D., (2021). The Lineaments as one of the Precursors of Earthquake: A Case Study of Tashkent Geodynamical Polygon in Uzbekistan. *Geodesy and Geodynamics*, Vol.12(6). 383-388 https://doi.org/10.1016/j.geog.2021.08.002.

[6] Bian, H. F., Zhang, S. B., Zhang, Q. Z. and Zheng, N. S., (2014). Monitoring Large-Area Mining Subsidence by GNSS based on IGS Stations. *Trans. Nonferrous Met. Soc. China*, Vol. 24, 514–519.

[7] Szczerbowski, Z. and Jura, J., (2015). Mining Induced Seismic Events and Surface Deformations Monitored by GPS Permanent Stations. *Acta Geodyn. Geomater*., Vol. 12, No. 3(179), 237–248. https://doi.org/10.13168/AGG .2015.0023.

[8] Ilieva, M., Rudzinski, L., Pawłuszek-Filipiak, K., Lizurek, G., Kudłacik, I., Tonda´s, D. and Olszewska, D., (2020). Combined Study of a Significant Mine Collapse Based on Seismological and Geodetic Data. *Remote Sens.*, Vol. 12(10). https://doi.org/10.3390/rs12101570.

[9] Fazilova, D., (2022). Uzbekistan Coordinate System Transformation from CS42 to WGS84 using Deformation Grid Model. *Geodesy and Geodynamics*, Vol. 13(1), 24-30. https://doi.org/10.1016/j.geog.2021.10.001.

[10] Herring, T. A., King, R. W., Floyd, M. A. and McClusky, S. C., (2018). *GAMIT Reference Manual, GPS Analysis at MIT, Release 10.7.* Cambridge, MA: Massachusetts Institute of Technology, 1-168. http://geoweb.mit.edu/gg/GAMIT_Ref.pdf.

[11] Dong, D., Herring, T. A. and King, R. W., (1998). Estimating Regional Deformation from a Combination of Space and Terrestrial Geodetic Data. *J. Geod*., Vol. 72, 200–214. https://doi.org/10.1007/s001900050161.

[12] Dubbini, M., Cianfarra, P., Casula, G., Capra, A. and Salvini, F., (2010). Active Tectonics in Northern Victoria Land (Antarctica) Inferred from the Integration of GPS Data and Geologic Setting. *J. Geophys. Res*., Vol. 115. https://doi.org/10.1029/2009JB007123.

[13] Petit, G. and Luzum, B., (2010). *IERS Conventions 2010 (IERS Technical Note 36)*, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 1-179.

[14] Beutler, G., Brockmann, E., Gurtner, W., Hugentobler, U., Mervart, L. and Rothacher, M., (1994). Extended Orbit Modeling Techniques at the CODE Processing Center of the International GPS Service for Geodynamics (IGS): Theory and Initial Results. *Manuscr. Geod.*, Vol.19, 367–386.

[15] Boehm, J., Niell, A., Tregoning, P. and Schuh, H., (2006). Global Mapping Function (GMF): A New Empirical Mapping Function Based on Numerical Weather Model Data. *Geophys. Res. Lett*., Vol. 33. https://doi.org/10.1029/2005GL025546.

[16] Saastamoinen, J., (1972). Atmospheric Correction for the Troposphere and Stratosphere in Radioranging of Satellites. *The Use of Artificial Satellites for Geodesy. Geophys. Monogr. Ser*., Vol.15, 247-251.

[17] Lyard, F., Lefèvre, F., Letellier, T. and Francis, O., (2006). Modelling the Global Ocean Tides: A Modern Insight from FES2004. *Ocean Dynamics*, Vol. 56, 394–415. https://doi.org/10.1007/s10236-006-0086-x.

[18] Herring, T. A., Floyd, M. A., King, R. W. and McClusky, S. C., (2015). *GLOBK Reference Manual, Global Kalman Filter VLBI and GPS Analysis Program, Release 10.6.* Cambridge, MA: Massachusetts Institute of Technology, 1-95. http://geoweb.mit.edu/gg/GLOBKRef.pdf.

[19] Altamimi, Z., Rebischung, P., Métivier, L. and Collilieux, X., (2016). ITRF2014: A New Release of the International Terrestrial Reference Frame Modeling Nonlinear Station Motions. *Journal of Geophysical Research: Solid Earth,* Vol. 121(8), 6109–6131. https://doi.org/10.1002/2016jb013098.

[20] Bagheri, A., Malekinezhad, H. and Afzal, P., (2016). A GIS-based Earthquake Hazard Assessment Using Bivariate Statistical Analysis and Spline Interpolation: A Case Study in Central Iran. *Geomatics, Natural Hazards and Risk*, Vol.7(5). 1705-1724.

[21] Boulaassal, A., Bouteldja, M. and Bouzid, A., (2018). GIS-Based Probabilistic Seismic Hazard Analysis Using Fuzzy Logic and Spline Interpolation. *Journal of Seismology*, Vol. 22(3). 757-776.

[22] Arslan, S., Yalçin, C. and Aksoy, E., (2019). GIS-Based Spatial Analysis of Seismic Hazard Using Spline Interpolation in the Region of Istanbul, Turkey. *Natural Hazards and Earth System Sciences*, Vol.19(9). 2021-2038.

[23] Republican Center for Seismic Prognostic Monitoring (RCSPM) database. [Online]. Available: https://rcsm.fvv.uz/ru/catalog_col. [Accessed January 07, 2022].