https://doi.org/10.51885/3134-8009_JES_2026_2_8
SRSTI 528.4:550.34

SURFACE DEFORMATION MONITORING IN EPICENTRAL ZONES OF UNDERGROUND NUCLEAR EXPLOSIONS USING GEODETIC METHODS

ЖЕРАСТЫ ЯДРОЛЫҚ ЖАРЫЛЫСТАРЫНЫҢ ЭПИЦЕНТРЛІК АЙМАҚТАРЫНДА ЖЕР БЕТІ ДЕФОРМАЦИЯСЫН ГЕОДЕЗИЯЛЫҚ ӘДІСТЕР АРҚЫЛЫ МОНИТОРИНГТЕУ

МОНИТОРИНГ ДЕФОРМАЦИЙ ПОВЕРХНОСТИ В ЭПИЦЕНТРАЛЬНЫХ ЗОНАХ ПОДЗЕМНЫХ ЯДЕРНЫХ ВЗРЫВОВ С ИСПОЛЬЗОВАНИЕМ ГЕОДЕЗИЧЕСКИХ МЕТОДОВ

A.T. Koishygarin [1], **Zh.K. Mukaliyev** [1*]
[1]Al-Farabi Kazakh National University, Almaty, Kazakhstan
*Corresponding author: Mukaliyev Zhandos Kairatovich, e-mail: zh.mukaliyev@kaznu.kz

Keywords:
Geodetic monitoring, surface deformation, underground nuclear explosions, epicentral zones, Semipalatinsk Test Site, ground subsidence, geodetic measurements.

ABSTRACT

This study examines geodetic monitoring of ground surface deformation in epicentral zones of underground nuclear explosions at the former Semipalatinsk Test Site. Underground nuclear explosions significantly alter geological structures and can lead to long-term deformation processes affecting the Earth's surface. The research focuses on the Balapan testing area, where underground nuclear tests were conducted in deep boreholes.

A geodetic observation network consisting of several benchmarks was established to monitor vertical displacements of the ground surface. High-precision leveling observations were performed using digital geodetic instruments to detect small elevation changes.

The analysis of monitoring data revealed measurable and persistent deformation processes occurring in the epicentral zone decades after the explosions. In particular, gradual subsidence of the ground surface was identified in the crater area, while other monitoring points exhibited stable uplift and fluctuating behavior. The magnitude of vertical displacements reached several millimeters per year, confirming the long-term geomechanical activity of the rock mass.

The results demonstrate the spatial heterogeneity of deformation processes and confirm the effectiveness of high-precision geodetic leveling for detecting millimeter-scale vertical displacements.

The scientific contribution of this study lies in the analysis of long-term observational data from the Balapan testing area and in the identification of deformation patterns specific to post-nuclear-test environments, which can support the development of monitoring systems and environmental safety assessments.

Түйінді сөздер:
Геодезиялық мониторинг, жер бетінің деформациясы, жер асты ядролық жарылыстары, эпицентрлік аймақтар, Семей Полигоны, жердің шөгуі, геодезиялық өлшеулер.

ТҮЙІНДЕМЕ

Бұл зерттеу Бұрынғы Семей Полигонындағы жерасты ядролық жарылыстарының эпицентрлік аймақтарындағы жер бетінің деформациясының геодезиялық мониторингін зерттейді. Жер асты ядролық жарылыстары геологиялық құрылымдарды айтарлықтай өзгертеді және Жер бетіне әсер ететін ұзақ мерзімді деформация процестеріне әкелуі мүмкін. Зерттеу жұмыстары терең ұңғымаларда жерасты ядролық сынақтары жүргізілген Балапан полигонына бағытталған.

Жер бетінің тік жылжуын бақылау үшін бірнеше эталондардан тұратын геодезиялық бақылау желісі құрылды. Биіктіктің кішігірім өзгерістерін анықтау үшін сандық геодезиялық құралдардың көмегімен жоғары дәлдіктегі нивелирлеу бақылаулары жүргізілді.

Мониторинг деректерін талдау жарылыстардан кейін ондаған жылдар өткен соң эпицентрлік аймақта болып жатқан өлшенетін және тұрақты деформация процестерін анықтады. Атап айтқанда, кратер аймағында жер бетінің біртіндеп шөгуі анықталды, ал басқа бақылау нүктелері тұрақты көтерілу мен құбылмалы мінез-құлықты көрсетті. Тік жылжулардың шамасы жылына бірнеше миллиметрге жетті, бұл тау жыныстарының массасының ұзақ мерзімді геомеханикалық белсенділігін растайды.

Нәтижелер деформация процестерінің кеңістіктік гетерогенділігін көрсетеді және миллиметрлік масштабтағы тік ығысуларды анықтау үшін жоғары дәлдіктегі геодезиялық нивелирлеудің тиімділігін растайды.

Бұл зерттеудің ғылыми үлесі Балапан сынақ аймағындағы ұзақ мерзімді бақылау деректерін талдауда және мониторинг жүйелері мен экологиялық қауіпсіздікті бағалауды дамытуға қолдау көрсете алатын ядролық сынақтардан кейінгі ортаға тән деформация заңдылықтарын анықтауда жатыр.

Ключевые слова:
Геодезический мониторинг, деформация поверхности, подземные ядерные взрывы, эпицентральные зоны, Семипалатинский испытательный полигон, просадка грунта, геодезические измерения.

АННОТАЦИЯ

В данном исследовании рассматривается геодезический мониторинг деформации земной поверхности в эпицентральных зонах подземных ядерных взрывов на бывшем Семипалатинском испытательном полигоне. Подземные ядерные взрывы существенно изменяют геологические структуры и могут привести к долгосрочным деформационным процессам, влияющим на земную поверхность. Исследование сосредоточено на испытательном полигоне Балапан, где проводились подземные ядерные испытания в глубоких скважинах.

Для мониторинга вертикальных смещений земной поверхности была создана геодезическая наблюдательная сеть, состоящая из нескольких контрольных точек. Высокоточные наблюдения за нивелированием проводились с использованием цифровых геодезических инструментов для обнаружения небольших перепадов высот.

Анализ данных мониторинга выявил поддающиеся измерению и устойчивые деформационные процессы, происходящие в эпицентральной зоне спустя десятилетия после взрывов. В частности, в районе кратера было обнаружено постепенное оседание поверхности земли, в то время как в других точках мониторинга наблюдались стабильные подъемы и колебания. Величина вертикальных смещений достигала нескольких миллиметров в год, что подтверждает долгосрочную геомеханическую активность горного массива.

Полученные результаты демонстрируют пространственную неоднородность деформационных процессов и подтверждают эффективность высокоточного геодезического нивелирования для определения вертикальных смещений миллиметрового масштаба.
Научный вклад этого исследования заключается в анализе данных долгосрочных наблюдений на испытательном полигоне Балапан и в выявлении закономерностей деформаций, характерных для условий после ядерных испытаний, которые могут помочь в разработке систем мониторинга и оценки экологической безопасности.

INTRODUCTION

Underground nuclear explosions are among the most intensive forms of anthropogenic disturbance affecting geological environments. They generate short-term shock effects and long-term geomechanical transformations, including the formation of underground cavities, fracturing of the surrounding rock mass, redistribution of stresses, and changes in the morphology of the ground surface (Glasstone & Dolan, 1977; Howard et al., 2004; Turchenko et al., 2023). These processes may continue for decades after detonation and can result in measurable vertical and horizontal displacements in epicentral zones.

The former Semipalatinsk Test Site in eastern Kazakhstan is one of the most important territories for studying the long-term consequences of nuclear testing. From 1949 to 1989, numerous nuclear tests were conducted at this site, including atmospheric, surface, and underground explosions (National Research Council, 2007; Panitskiy et al., 2023). Underground detonations were carried out in horizontal tunnels and deep vertical boreholes within several testing areas, including Degelen, Balapan, Sary-Uzen, and Telkem. These explosions caused significant disturbances in geological structures, affected rock mass stability, and altered the surface morphology of epicentral areas.

Post-explosion deformation may be expressed through subsidence, uplift, surface cracking, and crater formation. In some areas, large depressions developed above underground explosion cavities, indicating continuing geomechanical adjustment of the rock mass. For example, in the Balapan testing area, a crater more than 100 m in diameter and over 17 m deep formed several years after an underground detonation (Howard et al., 2004). Such cases demonstrate that deformation processes in post-nuclear-test areas are not limited to the immediate effects of explosions, but may also reflect delayed and long-term ground response.

Monitoring these processes is important for understanding post-explosion geodynamics and for assessing geological and environmental safety in former nuclear test territories. Geodetic methods provide a reliable basis for detecting small surface displacements with high accuracy. In particular, high-precision leveling makes it possible to determine vertical movements of the ground surface at the millimeter scale (Ghilani & Wolf, 2012). At the same time, modern geodetic and remote sensing techniques, such as GNSS observations and satellite radar interferometry, are increasingly used worldwide to complement traditional leveling and improve the spatial coverage of deformation monitoring (Massonnet & Feigl, 1998; Mukaliyev et al., 2024).

Despite previous studies on the geological and environmental consequences of nuclear testing, the long-term vertical deformation behavior of individual epicentral zones at the Semipalatinsk Test Site remains insufficiently interpreted from the perspective of repeated geodetic observations. In particular, the relationship between the organization of monitoring networks, the sign and magnitude of measured vertical displacements, and the temporal evolution of deformation trends requires further clarification.

The aim of this study is to evaluate the applicability of geodetic monitoring methods for detecting long-term surface deformation in epicentral zones of underground nuclear explosions at the former Semipalatinsk Test Site. The research is based on the analysis of vertical displacement measurements obtained in the Balapan testing area. The scientific novelty of the study lies in the interpretation of repeated high-precision leveling data for identifying temporal deformation patterns in a post-nuclear-test environment. Unlike previous works that mainly describe the general consequences of underground explosions, this study focuses on the geodetic assessment of vertical displacement dynamics and the practical organization of monitoring networks in epicentral zones. The results contribute to a better understanding of long-term geodynamic processes and support the development of continuous geodetic monitoring systems for geological and environmental safety assessment.

MATERIALS AND METHODS

The research was conducted within the territory of the former Semipalatinsk Test Site, located in eastern Kazakhstan. Particular attention was given to the Balapan testing area, where underground nuclear explosions were carried out in deep boreholes during the period of nuclear testing. The study focuses on the epicentral zone of borehole 1414, where long-term deformation of the Earth's surface has been observed.

Underground nuclear explosions generate complex geomechanical processes within the rock mass, including the formation of underground cavities, zones of fractured rocks, and redistribution of stresses in the surrounding geological structures. Over time, these processes may lead to subsidence, uplift, or irregular deformation of the ground surface above the explosion cavity. Therefore, monitoring such deformation processes requires a stable geodetic observation network capable of detecting small vertical displacements.

Study area and observation object

The object of monitoring is the epicentral zone of borehole 1414, located within the Balapan testing area. The underground nuclear test in this borehole was conducted on May 26, 1984, at a depth of approximately 489 m. Long-term geological processes after the explosion resulted in noticeable deformation of the ground surface around the epicentral zone (Yakovenko, 2013).

A crater formed above the underground explosion cavity as a result of collapse and compaction processes in the rock mass. The diameter of the crater currently exceeds 100 m, and its depth is more than 17 m. These morphological changes indicate the continuing influence of post-explosion geomechanical processes on the surface relief (Yakovenko, 2013).

Geodetic observation network

To monitor surface deformation, a geodetic observation network consisting of several benchmarks was established in the epicentral zone. The network includes observation points located both inside the deformation zone and outside it on relatively stable terrain.

The configuration of the monitoring network includes:

– one benchmark located near the center of the deformation zone (crater bottom);
– several benchmarks placed along the slopes of the crater;
– one reference benchmark located outside the deformation zone on stable terrain.

This configuration makes it possible to compare elevation changes between deforming parts of the crater and the stable reference area. Figure 1 shows the scheme of the geodetic observation network in the epicentral zone, including the spatial distribution of monitoring benchmarks and the reference point.

Geodetic monitoring was performed using high-precision leveling. Measurements were carried out with a SOKKIA SDL30 digital level and fiberglass leveling rods with RAB-coded scales. This equipment allows elevation differences to be measured with millimeter-level accuracy. The standard accuracy of the SOKKIA SDL30 digital level is approximately ±1.0 mm per 1 km of double-run leveling under normal field conditions.

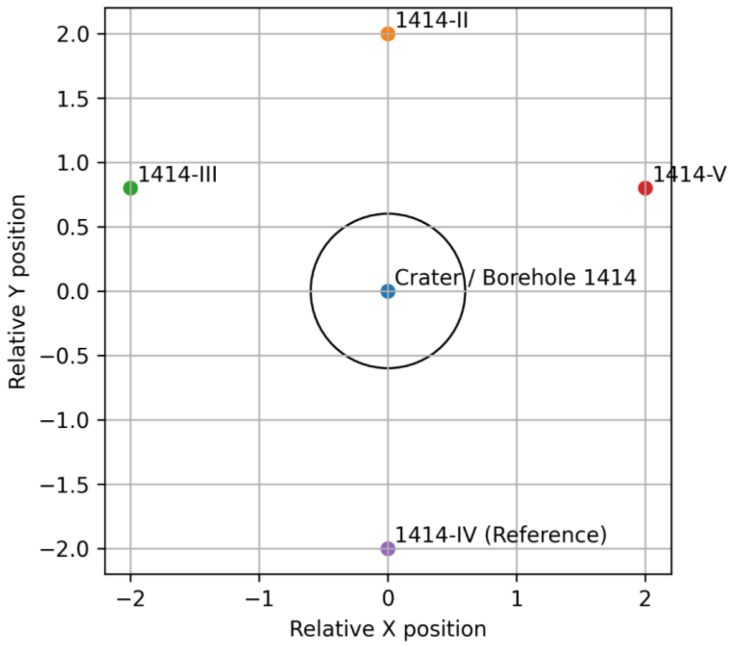

Figure 1. Scheme of geodetic observation network in the epicentral zone
Note – compiled by the authors

To reduce measurement errors, observations were conducted under stable weather conditions, using calibrated leveling rods and repeated measurement cycles. The estimated total error of elevation differences for individual benchmarks did not exceed ±2–3 mm. This level of accuracy is sufficient for detecting small vertical displacements in the epicentral zone. Therefore, the applied geodetic method provides reliable data for analyzing deformation processes.

The monitoring program included repeated measurement cycles performed periodically. The first observation cycle was conducted in 2009, when the initial elevations of all benchmarks were determined. Subsequent measurements were carried out in order to detect vertical displacements of the ground surface and to identify temporal deformation trends.

Figure 2 presents the integrated 3D monitoring scheme of borehole 1414. The figure illustrates the spatial arrangement of monitoring benchmarks, the crater geometry, and the reference point located on stable ground. This visualization helps to demonstrate the relationship between the observation points and the deformation zone.

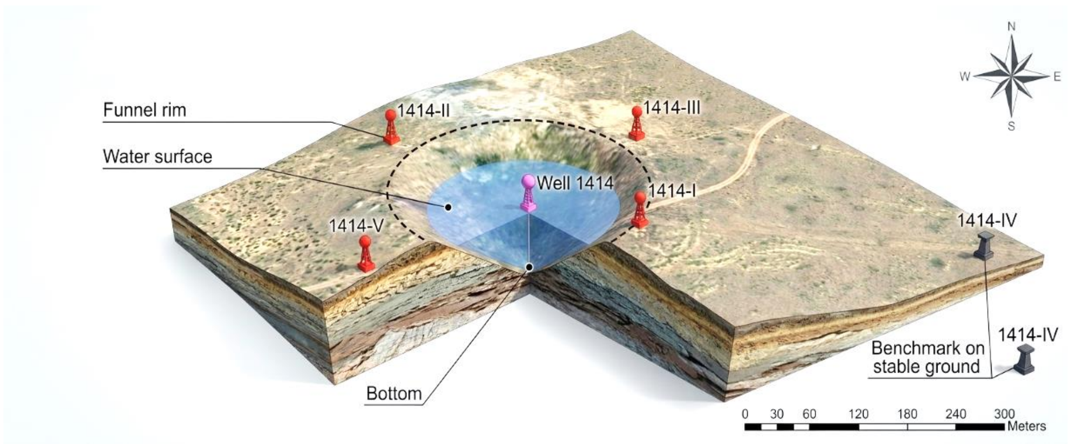

Figure 2. Integrated 3D monitoring scheme of funnel 1414.
Note – compiled by the authors

Data processing and deformation analysis

The monitoring data were processed in a conditional height system, where the benchmark located outside the deformation zone was used as the reference point. Elevation differences obtained from repeated measurements were analyzed to determine vertical displacements of monitoring benchmarks.

The data processing procedure included:

– calculation of elevation changes between observation periods;
– determination of vertical displacement values;
– identification of zones with maximum deformation;
– graphical analysis of deformation dynamics.

Positive displacement values were interpreted as relative uplift, whereas negative values were interpreted as subsidence. This approach made it possible to analyze not only the magnitude of deformation, but also the direction of vertical movement over time.

The results of repeated geodetic measurements are summarized in Table 1. The table presents elevation values and annual vertical displacement changes for monitoring benchmarks located within the epicentral zone.

Table 1. Elevation changes of monitoring benchmarks in the epicentral zone

Benchmark	Elev. 2020 (m)	ΔH 21–20 (mm)	Elev. 2021 (m)	ΔH 21–20 (mm)	ΔH 22–21 (mm)	Elev. 2022 (m)	ΔH 22–21 (mm)	Elev. 2023 (m)	ΔH 23–22 (mm)	Elev. 2023 (m)*	ΔH 24–23 (mm)	Trend
1414-II	305.62	–4	305.58	–4	–3	305.55	–3	305.49	–6	305.44	–5	Subsiding
1414-III	312.88	–3	312.85	–3	–6	312.79	–6	312.74	–5	312.74	–4	Declining
1414-IV	298.47	+4	298.51	+4	+4	298.55	+4	298.60	+5	298.60	+3	Rising
1414-V	289.24	+3	289.27	+3	–5	289.22	–5	289.18	–4	289.18	–2	Fluctuating
Note – compiled by the authors												

The data presented in Table 1 indicate different deformation trends within the epicentral zone. Benchmarks 1414-II and 1414-III show a consistent decrease in elevation, indicating subsidence. Benchmark 1414-IV demonstrates positive vertical displacement values, which may indicate local uplift or relative stabilization of the slope area. Benchmark 1414-V shows alternating positive and negative values, suggesting unstable or fluctuating deformation behavior.

In addition to classical geodetic leveling, modern deformation monitoring techniques such as Global Navigation Satellite Systems (GNSS) and Interferometric Synthetic Aperture Radar (InSAR) are widely used for detecting surface displacements. GNSS provides continuous three-dimensional positioning with high temporal resolution, while InSAR enables spatial analysis of ground deformation over large areas using satellite radar data. However, high-precision leveling remains one of the most accurate methods for detecting small vertical displacements at the local scale. For this reason, it was selected as the main method for the present study.

The obtained measurements allow the identification of deformation trends in the epicentral zone and the assessment of ground surface stability in areas affected by underground nuclear explosions. The combination of benchmark-based elevation measurements, error assessment, and temporal comparison provides a reliable basis for interpreting long-term deformation processes in the Balapan testing area.

RESULTS AND DISCUSSION

Geodetic monitoring data confirm ongoing deformation processes in the epicentral zones of underground nuclear explosions, even decades after detonation (Dickey et al., 1972). Analysis of repeated leveling measurements shows noticeable changes in the elevation of observation benchmarks located around the crater of borehole 1414.

The first observation cycle was conducted in 2009 and served as the initial reference for subsequent measurements (Nurpeisova et al., 2021). Comparison of elevation data obtained during the monitoring period revealed both uplift and subsidence processes in different parts of the observation network. During the first observation interval (2009–2010), slight uplift of the ground surface was recorded at several monitoring points located in the northwestern and eastern parts of the epicentral area (Kocharyan & Spivak, 2001). In particular, benchmark 1414-II showed an increase in elevation of approximately +3.4 mm, while benchmark 1414-III showed a slightly larger uplift of +5.9 mm.

However, subsequent observations revealed a different deformation trend (Ustavich et al., 2013). During the periods 2010–2011 and 2011–2012, a gradual decrease in elevation was observed at most monitoring points (Yakovenko & Ustavich, 2015). This indicates a general subsidence of the ground surface in the epicentral zone. The largest deformation was recorded at benchmark 1414-III, where the cumulative decrease in elevation reached approximately 8.8 mm during the monitoring period. Such deformation values confirm that the geological environment above the underground explosion cavity remains dynamically active.

Spatial analysis of the monitoring network shows that deformation intensity varies depending on the location of the benchmark relative to the crater center. Monitoring points located along the slopes of the crater demonstrate larger displacement values compared to the reference benchmark located outside the deformation zone (Nurpeisova et al., 2014). This pattern indicates that the main deformation processes are concentrated within the epicentral area where the underground cavity and fractured rock zone are located.

Table 2. Temporal dynamics of vertical displacement (ΔH, mm) of monitoring benchmarks in groups II, III, V and IV in the epicentral zone of borehole 1414 during the monitoring period 2020–2024

Group	2020	2021	2022	2023	2024
Group II	7.0	7.6	8.8	6.4	5.2
Group III	10.0	8.3	6.9	4.7	-3.0
Group V	8.0	6.1	4.2	3.3	-4.5
Group IV	6.8	5.5	4.6	3.5	-2.6
Note – compiled by the authors					

Table 2 illustrates the temporal dynamics of vertical displacement (ΔH) for different benchmark groups during the monitoring period 2020–2024, clearly demonstrating the transition from initial uplift to subsequent subsidence.

The data reveal a clear change in deformation behavior over time. In the earlier years (2020–2021), most monitoring groups are characterized by positive displacement values, indicating localized uplift of the ground surface.

However, in the later period (2022–2024), the displacement pattern shifts toward predominantly negative values, reflecting consistent subsidence across the epicentral zone. The largest negative values are observed in groups III and V, indicating more intensive deformation processes in these areas. The predominance of negative displacement values in recent years indicates that subsidence has become the dominant deformation process in the epicentral zone.

This transition from uplift to subsidence suggests a change in the dominant geomechanical processes. Initial uplift may be associated with residual stress redistribution and partial elastic recovery of the rock mass after the explosion, whereas subsequent subsidence reflects long-term compaction of fractured rock and gradual collapse of underground cavities.

The observed subsidence is controlled by several geomechanical processes occurring in the rock mass after the explosion. One of the most important mechanisms is the gradual collapse or compaction of underground cavities formed during the nuclear detonation. Over time, the surrounding rock mass undergoes stress redistribution, which leads to progressive deformation of the ground surface.

Another possible factor influencing surface deformation is the presence of fractured rock zones created by the explosion (Massé, 1981). These zones may experience gradual compaction and displacement under the influence of gravitational forces and long-term geodynamic processes. In addition, infiltration of groundwater into fractured zones may contribute to further weakening of the rock mass and acceleration of subsidence processes (Saharan, Mitri & Jethwa, 2006).

The results obtained from the geodetic monitoring network confirm that long-term deformation processes continue to develop in epicentral zones of underground nuclear explosions (Vincent, Foxall & Romano, 1997). Although the recorded displacement values are relatively small, their systematic character indicates the ongoing adjustment of the geological environment to the structural changes caused by the explosion.

Therefore, continuous geodetic monitoring remains an essential tool for assessing the stability of the ground surface in former nuclear test areas (Yadernye ispytaniya SSSR, 2000). The establishment of observation networks and periodic measurement of benchmark elevations provide valuable data for understanding long-term geodynamic processes and evaluating potential geological hazards in such territories (Busygina & Rykova, 2018).

The observed deformation patterns are consistent with results reported in international studies of underground nuclear test sites, where initial uplift is followed by long-term subsidence due to cavity collapse and rock mass compaction (Wang et al., 2018; Adushkin & Spivak, 2004).

CONCLUSION

The results of the conducted research demonstrate the significance of geodetic monitoring for the investigation of long-term deformation processes in the epicentral zones of underground nuclear explosions at the former Semipalatinsk Test Site. The establishment of a geodetic observation network made it possible to detect minor vertical displacements of the Earth’s surface and to assess deformation trends over time.

The analysis of repeated leveling observations carried out during the monitoring period showed that deformation processes continue to occur in the epicentral zone even decades after the underground nuclear explosion. During the initial observation period, slight uplift of the ground surface was recorded at several monitoring benchmarks. However, subsequent measurements revealed a gradual tendency toward subsidence in most of the benchmarks located around the crater.

The maximum recorded vertical displacement reached approximately 8.8 mm at one of the monitoring points located on the crater slope. These results indicate that the geological environment above the underground explosion cavity remains dynamically active. The observed surface subsidence may be associated with long-term geomechanical processes within the rock mass, including gradual compaction of fractured rocks and redistribution of stresses in the surrounding geological structures.

The conducted study confirms that high-precision geodetic monitoring is an effective method for detecting small-scale surface deformations and assessing ground surface stability in areas affected by underground nuclear explosions. Continuous monitoring of epicentral zones is essential for a better understanding of long-term geodynamic processes and for ensuring environmental safety in former nuclear testing areas.

Future research should focus on expanding the geodetic observation network and integrating geodetic monitoring data with remote sensing technologies and geomechanical modeling methods. Such an integrated approach will provide more comprehensive information on deformation processes and improve the reliability of geological hazard assessment in territories affected by underground nuclear explosions.

Overall, the obtained results highlight the importance of long-term monitoring for detecting delayed geomechanical effects in post-nuclear-test environments and for supporting scientifically grounded decisions related to environmental and geological safety.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

FUNDING: This research received no external funding.

INSTITUTIONAL REVIEW BOARD STATEMENT: Not applicable.

INFORMED CONSENT STATEMENT: This study did not involve human participants; therefore, informed consent was not required.

DATA AVAILABILITY STATEMENT: The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

ACKNOWLEDGEMENTS: The authors express their gratitude to colleagues and specialists who provided assistance during the geodetic observations and data processing. The authors also thank reviewers and experts for their valuable comments and suggestions that helped improve the quality of the manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES: No artificial intelligence (AI) technologies or generative AI tools were used in the preparation of this manuscript.

REFERENCES

Adushkin, V. V., & Spivak, A. A. (2004). Changes in properties of rock massifs due to underground nuclear explosions. Combustion, Explosion, and Shock Waves, 40, 624–634. https://doi.org/10.1023/B:CESW.0000048263.34894.58.

Adushkin, V. V., Kocharyan, G. G., & Novikov, V. A. (2016). Study of fault slip modes. Izvestiya, Physics of the Solid Earth, 52(5), 637–647.

Busygina, T. V., & Rykova, V. V. (2018). Analysis of publications on the Semipalatinsk Test Site using the Web of Science database and the CiteSpace program. Vestnik Natsional'nogo Yadernogo Tsentra Respubliki Kazakhstan, (4), 83–88. [in Russian]

Dickey, D. D., McKeown, F. A., & Bucknam, R. C. (1972). Preliminary results of ground deformation measurements near the CANNIKIN explosion. Bulletin of the Seismological Society of America, 62(6), 1505–1518.

Ghilani, C. D., & Wolf, P. R. (2012). Elementary surveying: An introduction to geomatics (13th ed.). Pearson.

Glasstone, S., & Dolan, P. J. (1977). The effects of nuclear weapons (3rd ed.). U.S. Department of Defense and U.S. Department of Energy.

Howard, B. J., Semioshkina, N., Voigt, G., Mukusheva, M., & Clifford, J. (2004). Radiostrontium contamination of soil and vegetation within the Semipalatinsk Test Site. Radiation and Environmental Biophysics, 43, 285–292. https://doi.org/10.1007/s00411-004-0261-8

Kocharyan, G. G., & Spivak, A. A. (2001). Movement of rock blocks during large-scale underground explosions. Part I: Experimental data. Journal of Mining Science, 37(1), 12–22.

Lukoshenko, S. N. (Ed.). (2010). Sbornik trudov Instituta radiatsionnoy bezopasnosti i ekologii za 2007–2009 gg. [Proceedings of the Institute of Radiation Safety and Ecology for 2007–2009]. Dom Pechati. [in Russian]

Massé, R. P. (1981). Review of seismic source models for underground nuclear explosions. Bulletin of the Seismological Society of America, 71(4), 1249–1265.

Massonnet, D., & Feigl, K. L. (1998). Radar interferometry and its application to changes in the Earth's surface. Reviews of Geophysics, 36(4), 441–500. https://doi.org/10.1029/97RG03139

Mikhailov, V. N. (Ed.). (1997). Yadernye ispytaniya SSSR [Nuclear tests of the USSR]. Izdat. [in Russian]

Mukaliyev, Zh. K., Zhumatayeva, Zh. M., Assylbekova, A. A., Bekkuliev, A. A., Onalbayeva, D. S., & Rafikov, T. K. (2025). Remote sensing-based evaluation of land degradation and moisture variability in post-nuclear landscapes of Kazakhstan. Journal of Geography and Environmental Management. https://doi.org/10.26577/JGEM20257943

Mukaliyev, Zh., Assylbekova, A., Zhumatayeva, Zh., Azizov, E., & Rafikov, T. (2024). Creation of a database for the analysis of the lands of the Semipalatinsk Test Site. Bulletin of D. Serikbayev East Kazakhstan Technical University, (2), 75–82. https://doi.org/10.51885/1561-4212_2024_2_75

National Research Council. (2007). The containment of underground nuclear explosions. National Academies Press. https://doi.org/10.17226/1065

Nurpeisova, M. B., Kirgizbaeva, G. G., & Bekbassarov, Sh. Sh. (2014). Geodynamic monitoring of the Semipalatinsk Test Site territory. In 14th International Multidisciplinary Scientific GeoConference SGEM 2014 (Vol. 2, pp. 267–274). STEF92 Technology Ltd.

Nurpeisova, M. B., Umirbaeva, A. B., Donenbaeva, N. S., et al. (2020). Ground benchmark for geodetic measurements. Patent RK No. 4700.

Nurpeisova, M. B., Umirbaeva, A. B., Fedorov, E. V., & Miletenko, N. A. (2021). Assessment of deformed and radiological state territory based on integrated monitoring. Eurasian Mining, (1), 80–84. https://doi.org/10.17580/em.2021.01.17

Panitskiy, A., Syssoeva, Y., Baigazy, S., Kunduzbayeva, A., Kenzhina, L., Polivkina, Y., Larionova, N., Krivitskiy, P., & Aidarkhanova, A. (2023). Vertical distribution of radionuclides in soil at the Semipalatinsk Test Site beyond its test locations. PLoS ONE, 18(1), Article e0278581. https://doi.org/10.1371/journal.pone.0278581

Saharan, M., Mitri, H., & Jethwa, J. (2006). Rock fracturing by explosive energy: Review of state-of-the-art. Fragblast, 10(1), 61–81.

Turchenko, D. V., Aidarkhanov, A. O., Aidarkhanova, A. K., Aktayev, M. R., Dashuk, A. L., & Kruglykhin, A. A. (2023). Research into the current radiological state of air and monitoring observations on STS and the adjacent territory. Journal of Environmental Radioactivity, 264, Article 107199. https://doi.org/10.1016/j.jenvrad.2023.107199

Ustavich, G. A., Yakovenko, Yu. Yu., Yakovenko, A. M., & Poshivaylo, Ya. G. (2013). The composition of geodetic and cartographic works in studying nuclear explosion sites at the Semipalatinsk Test Site. Geodeziya i Kartografiya, (4), 2–6.

Vincent, P., Foxall, B., & Romano, J. (1997). Analysis, comparison, and modeling of radar interferometry data of surface deformation signals associated with underground explosions, mine collapses and earthquakes. Phase I: Underground explosions, Nevada Test Site (UCRL-ID-128403). Lawrence Livermore National Laboratory.

Wang, T., Shi, Q., Nikkhoo, M., Wei, S., Barbot, S., Dreger, D., Bürgmann, R., Motagh, M., & Chen, Q. (2018). The rise, collapse, and compaction of Mt. Mantap from the 3 September 2017 North Korean nuclear test. Science, 361(6398), 166–170. https://doi.org/10.1126/science.aar7230

Yakovenko, A. M. (2013). K provedeniyu geodezicheskogo monitoringa v epitsentral'nykh zonakh raneye provedennykh podzemnykh yadernykh vzryvov na byvshem Semipalatinskom ispytatel'nom poligone [On conducting geodetic monitoring in epicentral zones of underground nuclear explosions at the former Semipalatinsk Test Site]. Vestnik Natsional'nogo Yadernogo Tsentra Respubliki Kazakhstan, (3), 23–26. [In Russian]

Yakovenko, A. M., & Ustavich, G. A. (2015). Deformation monitoring of ground surface at test wells at Semipalatinsk Nuclear Test Site. Izvestiya Vuzov. Geodeziya i Kartografiya, (S5), 146–151.

Yadernye ispytaniya SSSR. (2000). Yadernye vzryvy v interesakh narodnogo khozyaystva i nauchnykh issledovaniy [Nuclear explosions for national economy and scientific research] (Vol. 4). RFNC-VNIIEF. [In Russian]

Авторлар туралы мәліметтер
Информация об авторах
Information about authors

Қойшығарин Айбек – PhD докторант, оқытушы; әл-Фараби атындағы Қазақ ұлттық университеті, Алматы қ., Қазақстан.
Койшыгарин Айбек – PhD докторант, оқытушы; Казахский национальный университет им. Аль-Фараби, г. Алматы, Казахстан
Koishygarin Aibek – PhD doctoral student, lecturer; Al-Farabi Kazakh National University, Almaty, Kazakhstan.
e-mail: aibek-1-89@mail.ru
ORCID: https://orcid.org/0009-0009-3437-8865

Мукалиев Жандос Кайратович – техника ғылымдарының магистрі, әл-Фараби атындағы Қазақ ұлттық университеті, Алматы қ., Қазақстан,
Мукалиев Жандос Кайратович – магистр технических наук, Казахский национальный университет им. Аль-Фараби, г.Алматы, Казахстан,
Mukaliyev Zhandos – Master of Technical Sciences, Al-Farabi Kazakh National University, Almaty, Kazakhstan,
e-mail: Zh.mukaliyev@kaznu.kz
ORCID: https://orcid.org/0000-0001-9292-7468