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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылыметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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MONITORING OF LAND SURFACE SUBSIDENCE DURING INTENSIVE DEVELOPMENT OF OIL FIELDS

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Abstract. *Relevance.* The article focuses on the study of geodynamic processes associated with the development of hydrocarbon deposits in western Kazakhstan. *Objective.* Enhancing the safety of oil field development through systematic monitoring and forecasting of hazardous geodynamic processes and related phenomena. *Materials and methods* A comprehensive research methodology was used to carry out the study, including the analysis and generalization of national and international experience in geodynamic research; repeated geodetic observations of deformations in undermined areas using modern geodetic instruments; assessment of the influence of various factors on ground surface

subsidence through theoretical calculations of seam roof subsidence; consideration of the impact of deposit development intensity on ground surface displacement; and formulation of conclusions regarding the nature of geodynamic processes in the study area. *Results*. The results of comprehensive monitoring of land surface and Caspian Sea coastline deformation are presented using areas of intensive and large-scale subsoil development as case studies. The need for integrated territorial monitoring and geodetic monitoring on the Buzachi Peninsula is substantiated. To investigate natural geodynamic processes and phenomena, as well as to identify the impact of technogenic factors on crustal dynamics, a geodynamic testing ground has been established in areas of intensive hydrocarbon development in western Kazakhstan. This testing ground includes stationary high-precision leveling, satellite, gravimetric, and seismic stations located within the Karazhanbas, Kalamkas, and North Buzachi fields. Geodynamic monitoring using modern geodetic instruments improves the accuracy and efficiency of determining subsidence parameters, ensuring maximum safety and economic efficiency in the overall development of oil and gas fields. Results of the study were implemented at the existing Geoservice-S LLC during the implementation of the project «Monitoring deformation processes of the earth's surface during the development of oil fields in Western Kazakhstan» and were used in the educational process at Satbayev University, as well as at Al-Farabi Kazakh National University.

Keywords: hydrocarbon deposits, land surface, subsidence, reservoir roof, reservoir pressure, geodynamic test site, geodetic monitoring, GPS observations, geodynamic process modeling

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МҰНАЙ КЕН ОРЫНДАРЫН ҚАРҚЫНДЫ ИГЕРУ КЕЗІНДЕГІ ЖЕР БЕТІНІҢ ШӨГУІН МОНИТОРИНГТЕУ

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Аннотация. *Өзектілігі.* Мақала Қазақстанның батыс өңіріндегі көмірсутек кен орындарын игеру барысында орын алатын геодинамикалық үдерістерді зерттеуге арналған. *Мақсаты*. Қауіпті геодинамикалық үдерістер мен құбылыстарды мониторингтеу және болжау арқылы мұнай кен орындарын игерудің қауіпсіздігін арттыру. *Материалдар мен әдістер***.** Жұмысты орындау барысында кешенді зерттеу әдісі қолданылды, оның ішінде: геодинамикалық зерттеулер бойынша отандық және шетелдік тәжірибені талдау және жинақтау; заманауи геодезиялық аспаптарды қолдана отырып, игеріліп жатқан аумақтардағы деформацияларды қайталама геодезиялық бақылау; қабат төбесінің шөгуін теориялық есептеу арқылы жер бетінің шөгу үдерісіне әртүрлі факторлардың әсерін бағалау; кен орындарын игеру қарқындылығының жер бетінің ығысуына әсерін ескеру; қарастырылып отырған аумақтағы геодинамикалық үдерістердің сипаты бойынша қорытындылар жасау. *Нәтижелері. Қарқынды* және ауқымды жер қойнауын игеру учаскелері мысалында жер беті мен Каспий теңізінің жағалау сызығының деформацияларын кешенді мониторингтеу нәтижелері ұсынылған. Сондай-ақ Бозашы түбегінде аумақты кешенді геодезиялық мониторингтеудің қажеттілігі негізделген. Табиғи геодинамикалық үдерістер мен құбылыстарды зерттеу және техногендік факторлардың жер қыртысының динамикасына әсерін анықтау мақсатында Батыс Қазақстандағы көмірсутек кен орындарын қарқынды игеру аймақтарында жоғары дәлдікті нивелирлік, спутниктік, гравиметриялық және сейсмикалық станциялардан тұратын геодинамикалық полигон құрылған. Ол Қаражанбас, Қаламқас, Солтүстік Бозашы кен орындары аумағында орналасқан. Заманауи геодезиялық аспаптарды қолдана отырып жүргізілетін геодинамикалық мониторинг жер бетінің шөгу параметрлерін анықтаудың дәлдігі мен жеделдігін арттырады, сондай-ақ мұнай-газ кен орындарын игерудің қауіпсіздігі мен экономикалық тиімділігін қамтамасыз етеді. Зерттеу нәтижелері «Геосервис-С» ЖШС-де «Батыс Қазақстандағы мұнай кен орындарын игеру кезінде жер бетінің деформациялық үдерістерін мониторингтеу» жобаларын орындау барысында енгізілген, сондай-ақ Satbayev University мен әл-Фараби атындағы ҚазҰУ оқу үдерісінде қолданылуда.

Түйін сөздер: көмірсутек кен орындары, жер беті, шөгу, қабат төбесі, қабаттық қысым, геодинамикалық полигон, геодезиялық мониторинг, GPS бақылаулар, геодинамикалық үдерістерді модельдеу

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МОНИТОРИНГ ОСЕДАНИИ ЗЕМНОЙ ПОВЕРХНОСТИ ПРИ ИНТЕНСИВНОМ ОСВОЕНИИ НЕФТЯНЫХ МЕСТОРОЖДЕНИЙ

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Аннотация. *Актуальность.* Статья посвящена исследованию геодинамических процессов, возникающих при разработке месторождений углеводородов в западных регионах Казахстана. Интенсивное освоение нефтегазовых месторождений может сопровождаться изменением напряжённо-деформированного состояния горного массива и оседанием земной поверхности, что обусловливает необходимость систематического геодинамического мониторинга. *Цель.* Повысить безопасность разработки нефтяных месторождений на основе мониторинга и прогнозирования опасных геодинамических процессов и явлений. *Материалы и методы* В исследовании применён комплексный подход, включающий анализ и обобщение отечественного и зарубежного опыта проведения геодинамических исследований; повторные геодезические наблюдения за деформациями подрабатываемых территорий с использованием современных

измерительных приборов; оценку влияния различных факторов на оседание земной поверхности посредством теоретического расчёта деформаций кровли пласта; учёт влияния интенсивности разработки месторождений на смещение земной поверхности; определение характера геодинамических процессов на исследуемой территории. *Результаты*. Представлены результаты комплексного мониторинга деформаций земной поверхности и береговой линии Каспийского моря на примере участков интенсивного и масштабного освоения недр. Обоснована необходимость комплексного геодинамического и геодезического мониторинга территории полуострова Бузачи. Для исследования природных геодинамических процессов и явлений, а также выявления влияния техногенных факторов на динамику земной коры в районах интенсивной разработки месторождений углеводородов Западного Казахстана создан геодинамический полигон. Он включает сеть стационарных высокоточных нивелирных, спутниковых, гравиметрических и сейсмических станций, расположенных в районах месторождений Каражанбас, Каламкас и Северные Бузачи. Проведение геодинамического мониторинга с использованием современных геодезических приборов позволяет повысить достоверность и оперативность определения параметров оседания земной поверхности, а также способствует повышению безопасности и экономической эффективности освоения нефтегазовых месторождений. Результаты исследования внедрены в деятельность ТОО «Геосервис-С» при выполнении проекта «Мониторинг деформационных процессов земной поверхности при освоении нефтяных месторождений Западного Казахстана», а также используются в учебном процессе Satbayev University и Казахского национального университета имени аль-Фараби.

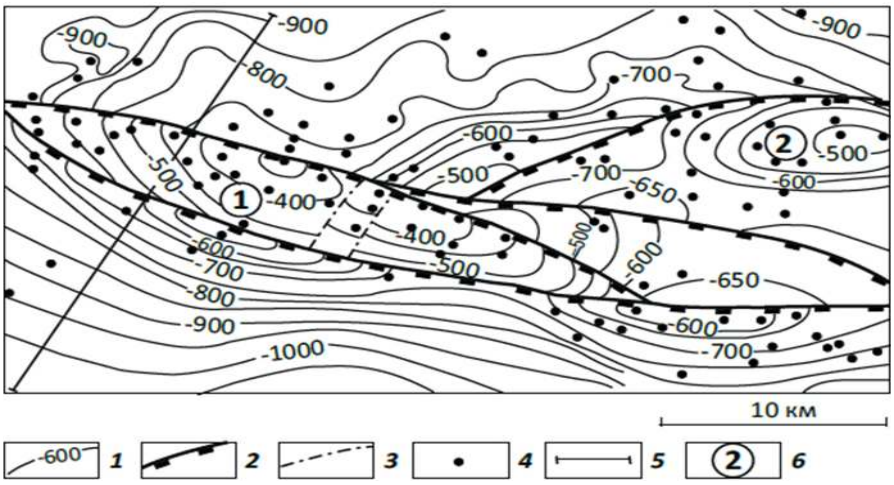
Ключевые слова: месторождения углеводородов, земная поверхность, оседание, кровля пласта, пластовое давление, геодинамический полигон, геодезический мониторинг, GPS наблюдения, моделирование геодинамических процессов

Introduction. Subsoil of the western region of the Republic of Kazakhstan is rich in hydrocarbon deposits. Large-scale oil and gas development leads to intense ground movements, both within localized areas and within individual structural elements. This results in the distortion of drilled wells, rupture of oil, gas, and water pipelines, and disruption of railways, highways, underground utilities, and engineering structures, which in turn leads to significant economic losses.

During development of hydrocarbon deposits in many oil and gas basins worldwide, intense and even catastrophic geodynamic phenomena associated with oil and gas production have been recorded.

Examples include strong earthquakes recorded at gas fields such as Gazli in Uzbekistan, Lacq in France, Strachan in the Snipe Lake area of Canada, Fashing in the USA, and several others. These phenomena are a direct consequence of changes in the geodynamic regime of the geological environment under the influence of large-scale subsoil development. This conclusion is convincingly supported by

the results of experimental studies conducted on the natural–technical system of the Caspian zone by Satbayev University in cooperation with Geoservice-S LLP within the framework of the «Program for integrated geodynamic monitoring of natural and technogenic processes at hydrocarbon fields for the periods 2012–2019 and 2023–2025



1 — stratoisohypses, m; 2 — thrusts; 3 — strike-slip faults; 4 — wells; 5 — seismic section line; 6 — anticlines (1 — Karazhanbas, 2 — Northern Buzachi)

Figure 1. Depth map over the Jurassic Bottom covering (Karazhanbas and North Buzachi anticlines).

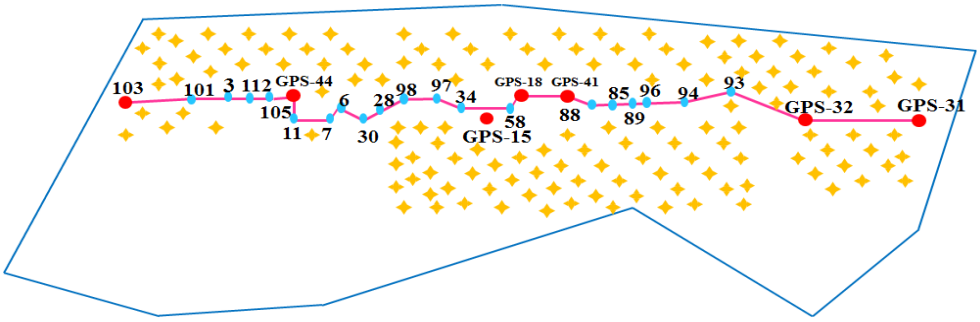
Materials and methods. At the Northern Buzachi deposit, geodetic monitoring and analysis of ground movement were sporadic. Comprehensive ground movement observations were conducted by the GEOKEN Scientific and Production Center from 2007 to 2010 (Saparbekova et al., 2015; Solyanoy, 2018). These comprehensive ground movement monitoring efforts included ground-based, satellite, and space-based observations.

Establishment of geodynamic testing site. In accordance with Work program for geodynamic monitoring at the Northern Buzachi Field, Satbayev University continued work on developing the geodynamic testing site, as well as organizing and conducting comprehensive monitoring of natural and man-made processes using expanded set of measurement methods. Results obtained are planned to be used in addressing industrial and environmental safety at the long-running oil fields of the Buzachi Peninsula (Nurpeisova et al., 2016; Nosirov et al., 2018).

Figure 3 shows the layout of leveling stations within the deposit area. Profile 5-5 is oriented along the strike of the deposit. Previously, 12 primary and 7 additional leveling stations were established along this profile. In addition, 4 GPS stations were included in the leveling traverse. Total number of stations along profile 5-5 is 19 (Table 1).

Table 1. Characteristics of the leveling profile 5 – 5.

№№ Profile	Profile length (km)	Number of points	Number of leveling cycles	Average distance between points, m
5-5	24, 7	19	6	130



..– *leveling points combined with gravimetric points.*

points; - *wells.*

Figure 3. Layout of points on the territory of the Northern Buzachi deposit.

Highly accurate GPS measurements. In 2024, high-precision GPS measurements continued at the Severnye Buzachi deposit (the third monitoring cycle). Measurements were conducted at four GPS stations (including one GPS-5 control station and three regular stations) within the deposit's boundaries. Four sets of GPS equipment were used for the GPS measurements: dual-frequency Leica GS16 receivers. Final benchmark elevations were determined using trigonometric leveling with a TS15 Plus electronic total station.

Positioning of four long-term GPS points at the field was determined statically using groups of four receivers, with observations referenced to the GPS-5 base station. Only two observation sessions were conducted at the site, second session serving as a control. Observations were conducted statically, with synchronous sessions lasting at least 24 hours with a recording interval of 30 seconds.

Based on measurement results and considering accuracy assessment, catalog of GPS point coordinates for Cycle 3 in 20124 (Table 2) and diagram of actual locations of GPS points within the Severnye Buzachi field were compiled (Seytmuratova et al., 2018; Zhantaev et al., 2012).

Table 2. List of GPS coordinates based on GPS measurements Northern Buzachi deposit, August 2024.

№	Item number	Rectangular coordinate, m UTMN Zone 39		Height, m
		X	У	
1	1	4966425,4450	733801,9124	165,8928
2	2	4969697,1623	737091,9870	155,4020
3	3	4969541,5278	733177,5372	168,4864
4	5	4972408,7700	730245,3000	161,4100

Quality of measurements was assessed based on discrepancies observed at the points where the observation sessions overlapped. A total of three control measurements were carried out. The standard error of a single coordinate measurement was ±0.8 mm, while the standard error for height measurements was ±1.3 mm. These results confirm the high accuracy of third GPS measurement cycle and allow its data to be reliably compared with results of previous measurement cycle.

Results and discussion. At the Northern Buzachi geodynamic testing site (GDS), Class II leveling was performed using a Leica WILD NA 3003 digital laser level with Invar rods using the dual leveling method in both forward and reverse directions. Level was set to accuracy tolerance of 0.4 mm, which corresponds to Class I leveling tolerances (Nurpeisova, Kenesbayeva, 2018).

Based on the results of first two precision leveling cycles along profile 1-1, which intersects the Northern Buzachi deposit across its strike, it is now possible to obtain initial estimates of the magnitude of modern vertical ground movements along this profile. Figure 4 shows a graph of modern vertical ground movements. Movement values are given in millimeters. Graph shows that the main part of the Buzachi deposit is characterized by ground subsidence. The maximum subsidence value is 12 mm. The average ground subsidence value is approximately 5 mm.

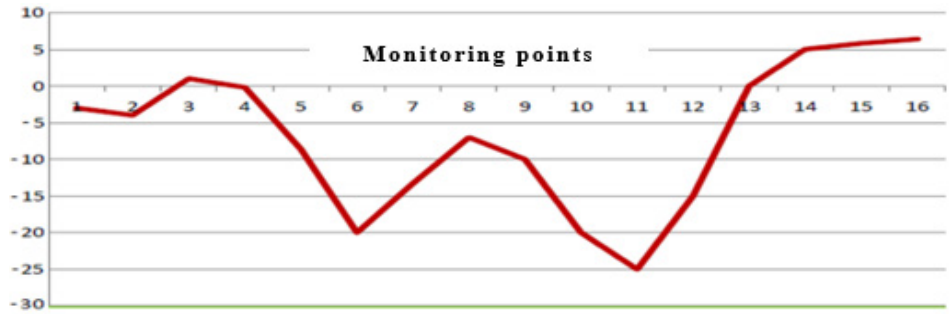


Figure 4. Graph of modern vertical movements of the earth's surface along profile 1-1.

Experience studying deformation processes at developed fields in the Republic of Kazakhstan shows that the most typical annual subsidence associated with hydrocarbon production is approximately 10 mm. Therefore, subsidence at the Northern Buzachi field should be considered entirely predictable. Results obtained allow us to draw a preliminary conclusion about the possible influence of development processes at the Northern Buzachi field on subsidence processes (Zhardaev, 2006).

Active subsidence of ground surface is observed at the deposit, particularly in the central part of the area. Two basins have been identified, located approximately in the middle of the site. The right basin is elliptical in shape, with a major semi-axis of approximately 840 m and a minor semi-axis of approximately 420 m. The

left basin is circular, with average radius of approximately 650 m. The rate of vertical movement has tended to increase over time. In the center of right basin, subsidence rate is 12.5 mm/year, while in the center of the left basin, it is 10 mm/year. Minor localized uplifts of ground surface are present in the eastern part of the deposit. Systematic, comprehensive monitoring of geodynamic processes is necessary to promptly identify abrupt changes in existing subsidence trend.

In the work (Kenesbaeva et al., 2019), based on space radar interferometry, results presented in Figure 5 were obtained. As can be seen from the map of accumulated subsidence, soil subsidence of up to 45 mm occurred over three years.

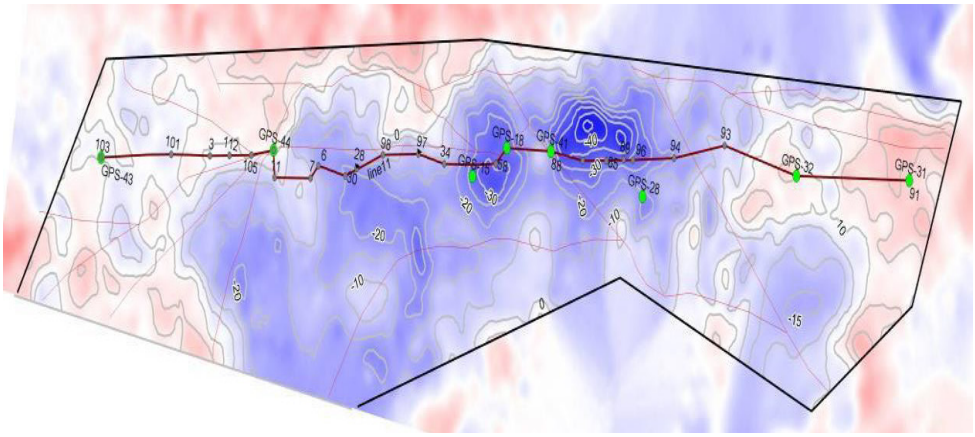


Figure 5. Map of accumulated subsidence over 3 years based on the research interval from March 2017 to February 2019.

Thus, intense subsidence processes are recorded within the deposit area, most pronounced in the central zone. Presence of two troughs, located approximately in the middle of the site, has been established. The right trough is nearly elliptical in shape, with a major axis of approximately 840 m and a minor axis of approximately 420 m. The left trough is characterized by a nearly circular shape with an average radius of approximately 650 m. Increase in the rate of vertical deformation over time is noted: in the center of the right trough, it reaches 12.5 mm/year, and in the center of the left trough, it is approximately 10 mm/year.

High-precision gravimetric measurements. In August 2025, second cycle of high-precision gravimetric measurements was conducted at the Northern Buzachi oil field using long-term gravimetric stations combined with leveling stations along profile 1-1. Locations of gravimetric stations combined with leveling stations are shown in Figure 6.

Before start of the field season, the gravimeters were tested at the Kapchagay - Almaty State gravimetric test site. Before work began at the Northern Buzachi field, cyclic measurements were taken over a 24-hour period. Standard deviations and nonlinearity of daily drifts do not exceed 0.01 mGal.

High-precision gravity measurements at the Northern Buzachi deposit were conducted from August 1 to 3, 2025, at 15 specially equipped stations within the deposit's geodynamic testing area. Long-term gravimetric stations were combined with leveling stations. The measurements were conducted using AutoGrav CG-5-091 automated gravimeters (Zholtaev et al., 2018).

All observations at the test site's points were conducted using the «central reference point» method. All observations were conducted in parallel with geodetic instruments. Trips lasted no more than three hours. Measurement quality control was maintained throughout shift by performing check measurements at one or two points in adjacent units, as well as by an independent check trip.

Field processing of measurement results was performed in parallel with the field measurements and included processing gravimetric measurement results, generating and updating graphs, assessing the quality of the linear drift breakpoint cruises, compiling a gravimetric point survey report, and assessing the quality of the gravimetric measurements. Results obtained in Cycle 2 were analyzed in comparison with Cycle 1. Graph of gravity changes (variations) from August 2016 to August 2018 was plotted along the profile line (Fig. 6).

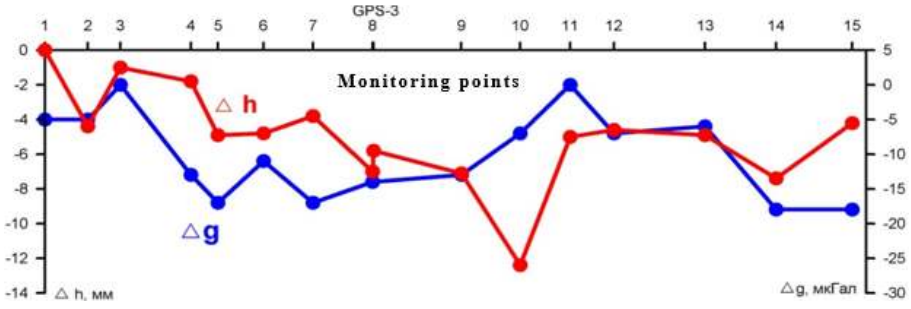


Figure 6. Graph of gravity variations (Δg) over an annual time interval along profile 1-1 of the field in comparison with the graph of modern vertical movements of the earth's surface (Δh).

Along profile 1-1, gravity variations range from -18 μGal to 0 μGal. The average gravity variation for the entire field is -10 μGal. Thus, the overall gravity variation background for the Northern Buzachi field (along profile 1-1) is negative over the annual time interval. The identified negative gravity variation background is typical, as it has been found for virtually all studied fields in the Republic of Kazakhstan (Kenesbayeva et al., 2019).

Development of a predictive geodynamic model for the Northern Buzachi field. Various approaches and algorithms are used to create predictive geodynamic models for hydrocarbon fields. To create a robust predictive model, we used both parametric spatiotemporal trend models and a method using the Knothe influence function, which considers the relationship between surface subsidence and reservoir compaction (Szostak-Chrzanowski et al., 2006).

(Knothe 1953) presented spatiotemporal subsidence trend model to describe

land subsidence due to gas production. In this method, the height Hi of reference point i at time t is determined as:

$$Hi,t = Hi,t_o + Zi,t\_t_o + \eta i,t, \quad (1)$$

where

Hi,t_o – initial height of the benchmark before the start of subsidence at the time t_o;

$Zi,\_t_o$ – vertical deformation due to gas production approximated by a spatiotemporal trend model;

$+ \eta i$, - noise caused by stochastic instability of the reference frame.

According to this trend model, the drawdown can be represented as:

$$zi,t-t0= v(t-t0)\exp(-12ri2)+\zeta t-t0 \quad (2)$$

where:

- t0<t<tend;
- t0, tend - the start time of subsidence and the end time of the subsidence model;
- ri - standardized radius from the center of the settling bowl to the point i;
- ζt−t0- noise factor that accounts for stochastic differences between the spatiotemporal trend model and the actual subsidence due to gas production.

Standardized radius is determined from following expression:

$$ri2=(xi-xc)2+(yi-yc)2r2, \quad (3)$$

where:

- *xc u yc* - coordinates of center of the settling bowl;
- *r* - radius from the center of the settling bowl to the inflection point

However, in the first case, it is necessary to introduce a coefficient that corrects for the subsidence bowl shape to improve the correlation between modeled and observed ground subsidence values. In the second case, it is necessary to more accurately determine the value of parameter a, which represents the percentage of reservoir compression transferred to the surface as subsidence. Therefore, when creating a robust model of ground subsidence, it is essential to primarily consider reservoir compaction. In general, magnitude of compaction depends on changes in formation pressure, reservoir thickness, and physical and mechanical properties of host reservoir rocks.

To construct a geodynamic model of the Northern Buzachi deposit, we used the spatial parametric model expressions (2) and (3) given above. After calculating subsidence and creating simulated trend models, we obtained subsidence troughs (of the earth's surface) closer to reality (Fig. 7).

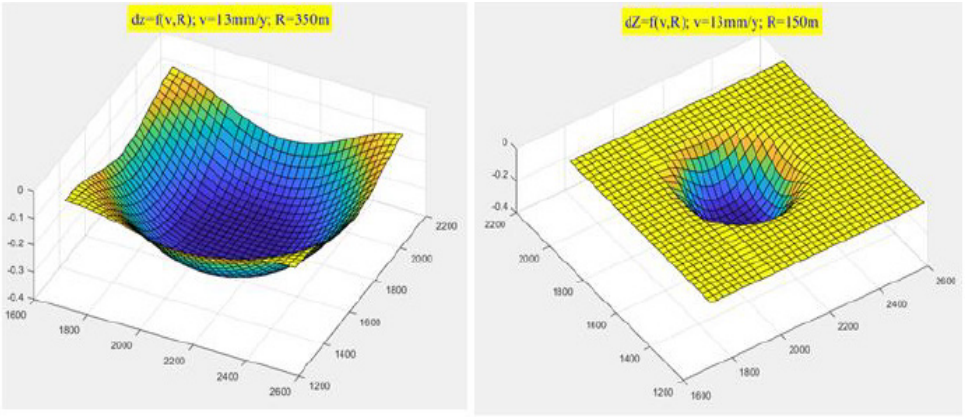


Figure 7. Subsidence bowls with radii of 350 m (left) and 150 m (right).

The analysis of the accuracy characteristics of the developed model demonstrated that an adequate description of ground surface deformation processes requires the application of a model based on the Knothe influence function, which takes into account the physical and mechanical properties of the reservoir, the depth of the productive formation, and changes in reservoir pressure. The development of this geodynamic model is the subject of a separate research project being conducted by researchers at Satbayev University.

Conclusions. A comprehensive analysis of domestic and international experience in geodynamic investigations related to the instrumental monitoring of deformations in undermined areas was carried out. Based on this analysis, a methodology for the integrated assessment and prediction of hazardous geodynamic processes within a geodynamic monitoring network was developed.

1. The methodology for repeated observations at the geodynamic monitoring network was improved through the integrated application of high-precision digital leveling, electronic total stations, and GNSS/GPS technologies. The proposed approach increases the accuracy and efficiency of determining ground surface subsidence and enhances monitoring performance through the automation of field measurements and computerized processing of geodetic data.

2. A comparative analysis of two monitoring cycles at the Severnye Buzachi oil field revealed a persistent trend of ground surface subsidence. According to repeated high-precision leveling along Profile 1–1, the maximum subsidence in the central part of the field reached 10–12 mm/year during the 2017–2019 observation period.

3. The results of repeated gravimetric observations showed a decrease in gravity along Profile 1–1. During the 2016–2018 period, the average gravity reduction relative to the peripheral parts of the field amounted to 15–17 μGal, indicating changes in the stress–strain state of the rock mass associated with the development of the oil field.

4. Repeated GNSS/GPS measurements confirmed the occurrence of general ground surface subsidence. The maximum vertical displacement of –4.3 mm was detected in the central and southern parts of the Severnye Buzachi oil field, which is consistent with the results obtained from high-precision leveling.

5. The developed simulation-based predictive model of ground surface subsidence, based on the adapted Knothe influence function, adequately describes the observed deformation trend and can be used to predict future subsidence and assess the geodynamic safety of oil and gas fields.

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