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Monitoring of displacements and deformations of the earth's surface at the Annensky field

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ABSTRACT

In connection with the ongoing depletion of mineral reserves located in relatively favorable conditions, at shallow depths, it is increasingly necessary to involve deposits located in complex mining and geological conditions; occurring at great depths, in complex, poorly studied and potentially dangerous conditions. The deposits developed by the underground method are no exception. Safe and efficient development of mineral deposits by underground method, occurring at great depths, is complicated by the fact that with an increase in the depth of mining, the nature of the course of deformation processes in the rock mass and the degree of their impact on the environment change. Studies of deformation processes, their control and forecast in many cases determine the efficiency and safety of the development of deposits of solid minerals. A practical forecast can be made as a result of continuous tracking in space and time of deformation processes. Currently, to determine the displacements and deformations of the earth's surface of the field, complex monitoring is used, which includes the following methods:
- methods of preliminary diagnostics of the rock massif;
- repeated high-precision leveling;
- satellite geodetic methods, primarily interferometry methods;
- other methods of instrumental observations in regional and local areas.

It should be noted that ground-based methods used for geomechanical monitoring of earth surface deformations, such as repeated geodetic leveling, as well as the use of satellite geodesy methods, do not fully reflect the temporal detail and spatial scale of the changes in the earth surface deformations. Today, the methods and technologies of space radar interferometry are of particular practical value, which make it possible to obtain areal estimates of vertical and planned displacements of the earth's surface with an accuracy of a few millimeters, regardless of illumination and cloudiness conditions. Space radar interferometry (CRI) is an effective tool for direct mapping of the earth's surface movements and deformations of structures over large areas of the study areas.

Keywords: monitoring, displacements of the earth's surface, deformation processes, high-precision leveling, radar interferometry.

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Introduction

The study of modern displacements and deformations requires high-precision geodetic measurements in the monitoring mode on the earth's surface of ore deposits [[1], [2], [3], [4]].

The sufficiently large experience of geodetic monitoring of deformation processes at deposits that is currently available shows [[5], [6], [7]] that subsidence of the earth's surface is widespread during long-term development of ore deposits and for the vast majority of the rate of technogenic subsidence is 1–2 cm/year, and the accumulated values do not exceed the first tens of centimeters. The consequences of such deformation processes can be the activation of landslide processes, the appearance of dangerous zones, displacement troughs [[8], [9]], etc.

At the Annensky field under study, as a result of the introduction of mining operations over many decades, vast areas of rock movement, subsidence and collapse of the earth's surface have formed, which continue to this day.

In 2004 and 2006, large collapses occurred in the Annensky mountain region as a result of the destruction of inter-chamber pillars (ICP) and failures of interlayers between worked out overlapping sloping deposits. The combined displacement trough covered an area of about 2 km along the strike of the Ann-2-I-II deposit and 0.6 km along the dip. Large rupture cracks formed on the earth's surface along the boundaries of the shear trough. Dips formed in the western part of the Annensky quarry. In the western part of the trough on the surface, in the zone of smooth shifts, the communications network continues to be used: a road, three collectors, a power line-35kV, a power line-6kV, a communication line.

In this regard, further mining of mineral reserves in such difficult conditions in the subsidence trough area was prohibited. However, significant mineral reserves lie under the zones of possible collapses, which can lead to unjustified losses of balance ore reserves.

The conclusions of studies previously conducted by various organizations turned out to be largely contradictory regarding the conduct of mining operations in the area of the formation of a huge trough, and therefore did not lead to unambiguous decisions on the development of mineral reserves.

Therefore, the purpose of this article is to determine the weakened zones on the earth's surface of the Annensky mine using high-precision leveling and space radar interferometry, which increases the efficiency and safety of field development.

Experimental part

Studies of deformation processes, their control and forecast in many cases determine the efficiency and safety of the development of deposits of solid minerals. A practical forecast can be made as a result of continuous tracking in space and time of deformation processes.

The system of complex monitoring of deformations of the earth's surface should contain the following basic methods [[10], [11]]:

Visual monitoring of rock movements

Methods of local observations of rock movements are used in studies of the stability of individual local sections of a rock mass due to the formation of continuous cracks of considerable length.

At the same time, the elements of occurrence of each crack at several points, the planned and height reference of measurement points, the nature of the surface of the cracks and the material filling them are subject to study.

For local observations, simplified mine surveying observations are used with the establishment of the boundaries of distribution and the type of deformations of rocks, the determination of the speed and magnitude of deformations, the identification of the critical value of displacements preceding the onset of the active stage and the pre-calculation of the development of deformations in time.

Repeated high-precision leveling

Repeated high-precision leveling is performed with the necessary and sufficient accuracy, which can be obtained using modern instruments and observation methods, which make it possible to most fully eliminate systematic leveling errors.

To perform leveling at the Anennsky mine, a modern Leica DNA03 digital level is used, designed for the most complex work requiring increased measurement accuracy, with a set of three-meter invar rails with a BAR code, which ensure leveling with an RMS error of measuring elevations of ±0.3 mm per 1 km double stroke.

Downhole reflectometry

TDR (Time Domine Reflectometry) downhole reflectometry methods are based on the use of a coaxial cable as a rock deformation detector. To do this, the cable is lowered into the drilled well and attached to the rock surrounding it with an expanding cement slurry. An electromagnetic signal is passed through the cable. In the process of shifting the rock mass, local deformations of the cable occur, which affect the passage of the electromagnetic signal in the places of its deformation. These places are fixed by the TDR reflector and displayed on the screen of an oscilloscope or computer.

Space radar interferometry

Space radar interferometry is the most important part of an integrated system for monitoring the state and building a continuous situational map of the earth's surface deformations.

To determine the values of the absolute values of the displacement of the earth's surface that occurred in the time period under study, for the correct application of SAR - interferometry methods, it is necessary to use a tandem pair of radar satellite images with a minimum value of the perpendicular baseline (distance between spacecraft) and having a minimum coherence value.

The discussion of the results

According to the data provided by the Annensky mine of Kazakhmys LLP, there are 4 profile lines on the earth's surface of the mine (Figure 1):

- profile line 65-65 bis;
- profile line 66;
- profile line 151;
- profile line 67.

According to the points of the network to determine the vertical movements of the earth's surface at the field, leveling of the II class of increased accuracy is designed. This technique provides for a combination of relatively fast observation with the achievement of a sufficiently high level of accuracy, which will reliably detect local anomalies in the vertical movements of the earth's surface with amplitudes of 3-5 mm and more. The practical accuracy of observations by the leveling method of the II class of increased accuracy is ±1 mm/km.

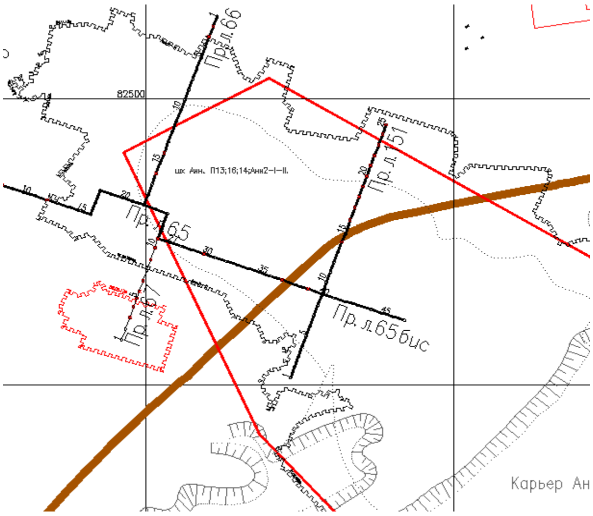

Figure 1 — Layout of profile lines at the Annensky field

Instrumental observations on the earth's surface of the Annensky mine have been carried out since 1976. Starting from 2009, in connection with the linking of elevations in all profile lines, the differences in measured observations were recalculated. Taking into account all linking marks, this research work provides an analysis of instrumental observations from 2011 to the present.

Profile line 65-65bis

On the profile line 65-65 bis, observations are made from 1 to 47 working benchmarks. In April 2009, in connection with the linking of the marks, they were recalculated from PP No. 146 for a difference of -0.0104 m. Also, the following observation benchmarks were excluded due to the destruction: 8, 12, 13, 25, 26, 37 and 39. In September 2010, due to linking, the marks were recalculated from the Sai triangulation to a difference of + 0.0099 m.

Taking into account all the recalculated marks, starting from 2011, a comparison was made of the excesses obtained as a result of the adjustment between the benchmarks of the profile line with the data of all cycles (Figure 2).

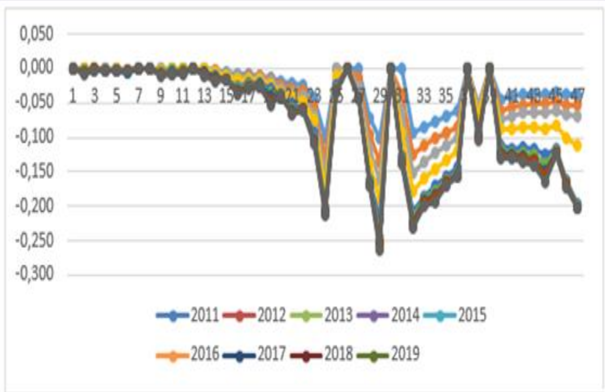

Figure 2 — Graph of subsidence according to the observational benchmarks of the profile line 65-65bis

Analysis of subsidence along the profile line 65-65bis, obtained from the results of multiple leveling, shows that intense subsidence is observed at working benchmarks 22, 23, 24, 28, 29 and 31. As can be seen from Figure 2, intense subsidence is noticeable in 2011 and 2015. It should be noted that with the conduct of mining operations and the development of the MCC in 2016, all the working benchmarks of the profile line 65-65bis were destroyed. In this regard, from 2016 to the present, instrumental observations are not possible in this area and require non-contact monitoring.

Profile line 66

On the profile line 66 observations are made from 1 to 19 working benchmarks. In April 2009, in connection with the linking of the marks, they were recalculated from PP No. 146 for a difference of -0.0104 m. Also, the following observation benchmarks were excluded due to the destruction: 2, 3, 13, 14 and 16. In September 2010, due to linking, the marks were recalculated from the Sai triangulation to a difference of + 0.0099 m.

Taking into account all the recalculated marks, starting from 2010, a comparison was made of the excesses obtained as a result of the adjustment between the benchmarks of the profile line with the data of all cycles (Figure 3).

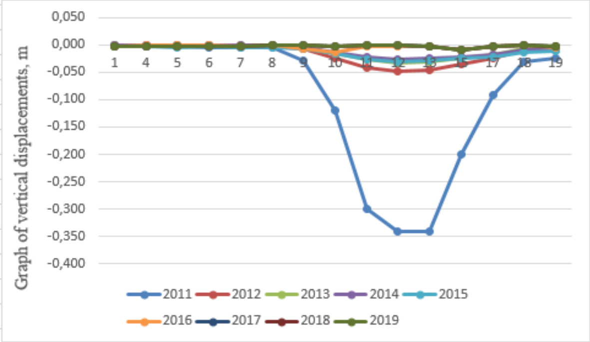

Figure 3 - Settling schedule along profile line 66 (according to observation benchmarks)

Analysis of subsidence along profile line 66, obtained from the results of multiple leveling, shows that intense subsidence is observed in the area of profile lines 10, 11, 12, 15 (Figure 3). Also, intensive subsidence is observed in 2011 and 2016 (Figure 3). For a more detailed analysis, it is necessary to carry out monitoring by the method of space radar interferometry.

Profile line 67

On the profile line 67 observations are made from 1 to 11 working benchmarks. In April 2009, due to the linking of elevations, they were recalculated from PP No. 146 (+25.501) for a difference of -0.0104 m. Also, the following observation benchmarks were excluded due to the destruction: 3, 4, 7, 9, 10 and 11. In September 2010, due to linking, the marks were recalculated from the Sai triangulation to a difference of + 0.0099 m.

Taking into account all the recalculated marks, starting from 2010, a comparison was made of the excesses obtained as a result of the adjustment between the benchmarks of the profile line with the data of all cycles (Figure 4).

Analysis of subsidence along the profile line 67, obtained from the results of multiple leveling, shows that intensive subsidence of the earth's surface is observed in 2010 (Figure 4). It should be noted that with the conduct of mining operations and the development of the ICP, 80% of the existing working benchmarks were destroyed. In this regard, for a more detailed analysis, it is necessary to monitor the method of space radar interferometry.

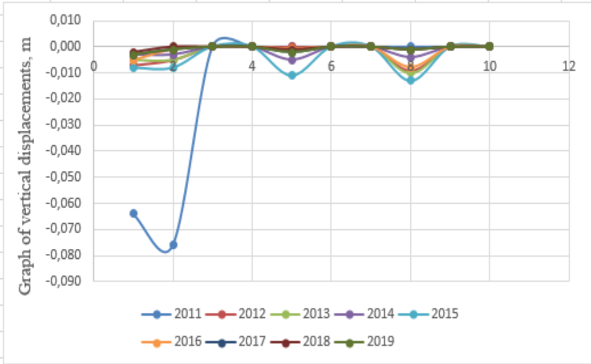

Figure 4 – Settling schedule along the profile line 67

Profile line 151

On the profile line 151 observations are made from 1 to 25 working benchmarks. In April 2009, due to the linking of elevations, they were recalculated from PP No. 146 (+25.501) for a difference of -0.0104 m. Also, the following observation benchmarks were excluded due to the destruction: 16, 17, 18, 19, 20, 21, 22, 23, 24 and 25. In September 2010, due to linking, the marks were recalculated from the Sai triangulation to a difference of + 0.0099 m.

Taking into account all the recalculated marks, starting from 2010, the comparison of the excesses obtained as a result of the adjustment between the benchmarks of the profile line with the data of all cycles was made (Figure 5).

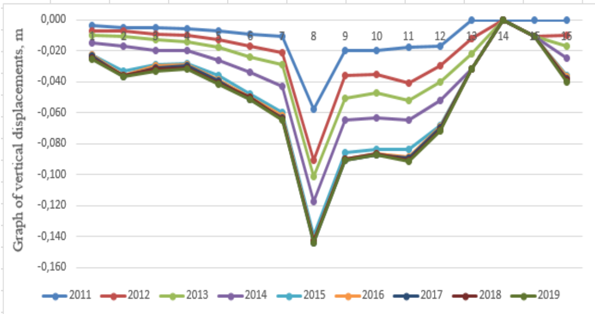

Figure 5 – Settling schedule along profile line 151 (according to observation benchmarks)

Analysis of subsidence along the profile line 151, obtained from the results of multiple leveling, shows that (Figure 5):

- The revealed features of modern vertical movements of the earth's surface in the area of the profile line, due to the mining of the MCC in the upper horizons and the mining of ores of the lower horizons, consist in constantly observed subsidence from the benchmark Rp No. 1 to the benchmark Rp No. 15. The most significant subsidence is observed in the area from the benchmark Rp No. 7 to Rp No.

12. The benchmark settlement rate is ≈ 50 mm per year.

For further study, the development of deformation processes, space radar surveys from the Sentinel satellite were used for the study area [12].

A pair of Sentinl-1B photographs with the following parameters are used for calculations:

- Measurement mode: Interferometric wide bandwidth (IW) measurement mode,
- Product: Level 1 Single View Complex (SLC),
- Incident angle: 29 - 46,
- Spatial resolution: 5 x 20 m,
- Sweep Width: 250 km,
- Subswath number: 2,
- Polarization: VV,
- Path: 22,
- Orbit: descending

For calculations, the following software products were considered: GMT5SAR and SNAP 6.0. Both of these programs differ in many ways, but they also have common features: they are open source software and allow you to process Sentinel-1 images.

After analyzing the advantages and disadvantages of software products, SNAP 6.0 software was chosen to perform the calculations. The input data processing algorithm in SNAP 6.0 software is as follows: registration, interferogram generation, interferogram filtering, unfolding phase and phase conversion to offsets, georeferencing.

The processing steps start with the selection and collection of the required data, usually in SLC (Single Look Complex) format, and end with a DEM or deformation map.

As a result of the work carried out, a map of displacements of the earth's surface of the territory of the Annensky mine was built, on which displacements of soils and soils in the subsidence trough up to 10 mm were recorded (Figure 6).

As a result of the work carried out, a map of displacements of the earth's surface of the territory of the Annensky mine was built.

Displacements of the earth's surface were determined and recorded according to observational data for the period using satellite images of 2018, 2019 and 2020 on the territory of the Annensky mine. The displacements took place in height both upwards during the formation of rock dumps, and downwards, as a result of the subsidence of the earth's surface. Comparative analysis showed that the obtained results are consistent with the data of ground-based measurements, as well as with the data of radar interferometry carried out by Sovzond LLC.

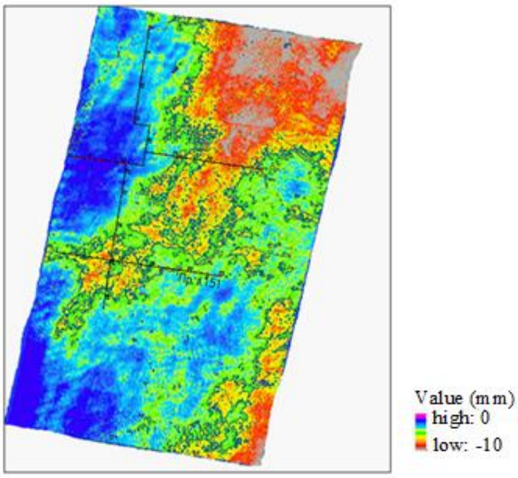

Figure 6 - Map of displacements of the earth's surface at the Annensky mine for the period 05.08.2020 – 06.25.2020.

To verify the results of SAR - interferometry, a planning map of ground mine surveying and geodetic observations was built in the study area of the Annensky mine. A comparative analysis of the displacements of the Earth's surface obtained by these methods was carried out, which showed their consistency. A continuous situational map of the problem areas of the Annenskoye field was compiled.

Also, the results of a comparative analysis of data on subsidence obtained by methods of differential interferometry and ground leveling are presented. Processed Sentinel data and profile lines 65 bis, 66, 67, 151 for the period 2018 to 2020 were selected as differential interferometry data. A detailed comparative analysis is shown in Figures 7-8.

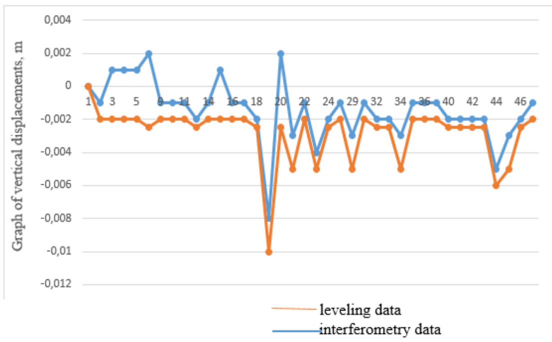

Figure 7 - Comparative analysis chart for profile line 65bis

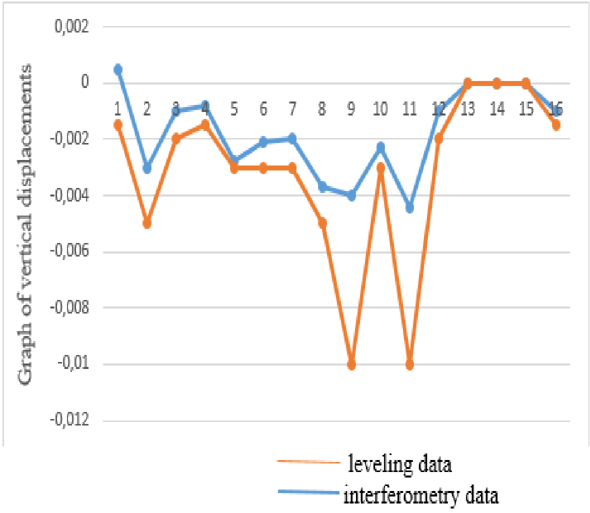

Figure 8 - Benchmarking chart for profile line 151

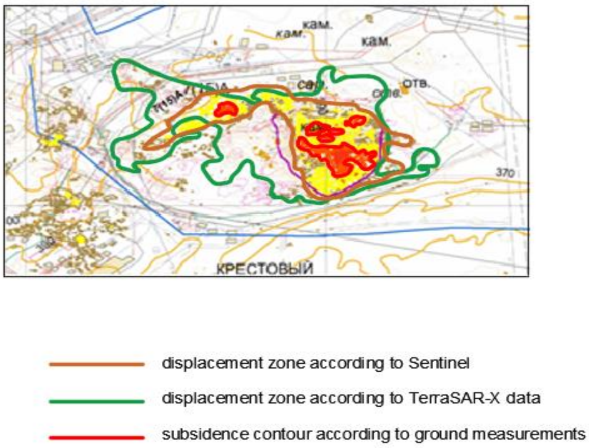

Figure 9 – Construction of a digital map of possible risk areas of subsidence of the earth's surface of the Annensky mine according to TerraSAR-X, Sentinel, ground measurements

Comparative analysis of the results of radar interferometry and showed the following.

1. The registered displacements of the earth's surface in the territory of the Annensky mine by the methods of radar and differential interferometry of Sovzond LLC, KazNITU-Grant, Sentinel are spatially confined to the sediment trough of the Annensky mine.

2. The zone of displacement (subsidence) of the earth's surface according to the data of the TerraSAR-X radar spacecraft, which has a higher spatial resolution (up to 1 meter), has more detailed detail and more accurately displays the contours of the intensive displacement trough obtained by ground surveying measurements.

3. The maximum absolute value of subsidence of the earth’s surface within the subsidence trough of the Annensky mine, obtained according to Sentinel data from 05/08/2020 to 06/25/2020, was 10 mm.

Based on the results of the above analysis and comparative graphs, a digital map of possible risk areas of displacement and subsidence of the earth's surface of the Annensky field was built (Figure 9).

In conclusion, we note that the accuracy of differential interferometry methods for solving the problem of monitoring the movements of the earth's surface depends on the parameters of satellite imagery.

Conclusions

As a result of the application of integrated monitoring of the Annensky mine, displacements of the earth's surface were determined and recorded according to observational data for the period using satellite images of 2018, 2019 and 2020. The maximum absolute value of subsidence of the earth's surface within the subsidence trough of the Annensky mine from October 2018 to August 2020 was 0.8 cm. The displacements took place in height both upwards during the formation of rock dumps, and downwards, as a result of the subsidence of the earth's surface.

Thus, the results of the conducted research allow developing additional minerals and increasing the efficiency of the mining enterprise.

Conflict of interests. On behalf of all authors, we declare that there is no conflict of interest.

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Анненский кенішіндегі жер бетінің жылжуын және деформациясын бақылау

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ТҮЙІНДЕМЕ

Салыстырмалы түрде қолайлы жағдайларда, таяз тереңдікте орналасқан пайдалы қазбалар қорларының сарқылуының жалғасуына байланысты күрделі тау-кен-геологиялық жағдайларда орналасқан, үлкен тереңдікте, күрделі, нашар зерттелген және ықтимал қауіпті жағдайларда орналасқан кен орындарын тарту қажет. Жер асты әдісімен игерілген кен орындары да ерекшелік емес. Үлкен тереңдікте жатқан пайдалы қазбалар кен орындарын жерасты әдісімен қауіпсіз және тиімді игеру тау-кен жұмыстарының тереңдігінің ұлғаюымен, тау-кен массивындағы деформация процестерінің жүру сипатымен және олардың әсер ету дәрежесімен қиындайды. Деформациялық процестерді зерттеу, оларды бақылау және болжау көп жағдайда қатты пайдалы қазбалар кен орындарын игерудің тиімділігі мен қауіпсіздігін анықтайды. Практикалық болжам деформация процестерін кеңістікте және уақытта үздіксіз қадағалау нәтижесінде жасалуы мүмкін. Қазіргі уақытта кен орнының жер бетінің жылжуын және деформациясын анықтау үшін келесі әдістерді қамтитын кешенді бақылау қолданылады:

- тау жыныстары массивін алдын ала бақылау әдістері;
- қайталанатын жоғары дәлдіктегі нивелирлеу;
- спутниктік геодезиялық әдістер, ең алдымен интерферометрия әдістері;
- аймақтық және жергілікті жерлерде аспаптық бақылаудың басқа әдістері.

Қайта геодезиялық нивелирлеу, сондай-ақ спутниктік геодезия әдістерін қолдану сияқты жер беті деформацияларының геомеханикалық мониторингі үшін қолданылатын жер үсті әдістері жер беті деформацияларында болған өзгерістердің уақытша егжей-тегжейі мен кеңістіктік масштабын толық көрсетпейтінін атап өткен жөн. Бүгінгі таңда ғарыштық радиолокациялық интерферометрияның әдістері мен технологиялары ерекше практикалық құндылыққа ие болып отыр, олар жарық пен бұлттылық жағдайларына қарамастан, бірінші миллиметрге дейінгі дәлдікпен жер бетінің тік және жоспарлы жылжуының алаңдық бағаларын алуға мүмкіндік береді. Ғарыштық радиолокациялық интерферометрия (ҒРИ) - зерттелетін аумақтардың үлкен аудандарындағы жер бетінің қозғалысы мен құрылымдардың деформациясын тікелей картаға түсірудің тиімді құралы.

Түйін сөздер: кешенді бақылау, жер бетінің жылжуы, деформациялық процестер, жоғары дәлдіктегі нивелирлеу, радиолокациялық интерферометрия.

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АННОТАЦИЯ

В связи с происходящим истощением запасов полезных ископаемых, расположенных в относительно благоприятных условиях, на небольших глубинах залегания, все чаще приходится вовлекать в добычу месторождения, расположенные в сложных горно-геологических условиях, залегающие на больших глубинах, в сложных, слабоизученных и потенциально опасных условиях. Не исключением являются и месторождения, разрабатываемые подземным способом. Безопасное и эффективное освоение месторождений полезных ископаемых подземным способом, залегающих на больших глубинах, осложняется тем, что с увеличением глубины ведения горных работ существенно изменяется характер протекания деформационных процессов в массиве пород и степень их влияния на окружающую среду. Исследования деформационных процессов, их контроль и прогноз определяют во многих случаях эффективность и безопасность разработки месторождений твердых полезных ископаемых. Практический прогноз может быть осуществлен в результате непрерывного слежения в пространстве и во времени за

деформационными процессами. В настоящее время для определения смещений и деформаций земной поверхности месторождения используют комплексный мониторинг, включающей в себя следующие методы:
- визуальный мониторинг подвижек горных пород;
- повторное высокоточное нивелирование;
- спутниковые геодезические методы, в первую очередь, методы интерферометрии;
- другие методы инструментальных наблюдений на региональных и локальных участках.

Следует отметить, что наземные методы, применяемые для геомеханического мониторинга деформаций земной поверхности, такие как повторное геодезическое нивелирование, а также применение методов спутниковой геодезии не полностью отражают временную детальность и пространственный масштаб произошедших изменений в деформациях земной поверхности. На сегодняшний день, особую практическую ценность приобретают методы и технологии космической радиолокационной интерферометрии, которые позволяют получать площадные оценки вертикальных и плановых смещений земной поверхности с точностью до первых миллиметров независимо от условий освещённости и облачности. Космическая радиолокационная интерферометрия (КРИ) представляет собой эффективное средство прямого картирования подвижек земной поверхности и деформаций сооружений на больших площадях исследуемых территорий.

Ключевые слова. комплексный мониторинг, смещения земной поверхности, деформационные процессы, высокоточное нивелирование, радарная интерферометрия.

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