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MODELING AND ANALYSIS OF EARTH'S SURFACE DEFORMATIONS VIA INSAR

The flooding of the Mirgalimsay Mine in the 1990s triggered the activation of hazardous geological processes in the adjacent area, including the city of Kentau. Subsidence, sinkholes and alterations in the hydrogeological regime are observed, posing significant risks to people and infrastructure. Consequently, monitoring of ground surface deformations using modern remote sensing techniques, such as Interferometric Synthetic Aperture Radar (InSAR), has become particularly relevant.

This paper presents an integrated monitoring methodology based on InSAR, including Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS) techniques, which enables assessment of vertical displacements with millimeter-level accuracy while minimizing the impact of atmospheric and orbital errors. Using Kentau as a case study, we demonstrate that this approach effectively identifies zones of intensive subsidence (up to 25 mm/year), validates data through ground-based measurements, and provides recommendations for ongoing monitoring and risk mitigation.

Keywords: *radar interferometry, interferogram, deformation, ground surface displacements, remote sensing methods, radar imagery*

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Introduction

Earth remote sensing is actively used in various sectors, including environmental monitoring, resource studies and emergency response management.

Synthetic Aperture Radar (SAR) has been utilized in Earth remote sensing for over thirty years. For a deeper understanding of the theoretical foundations underlying SAR image formation, one may refer to the works of H. Cruz et al. [1] as well as Y. K. Chan et al. [2]. The seminal contributions that elucidate the principles of SAR-based interferometry are found in the studies by C. Zhu et al. [3] and D. Ho Tong Minh et al. [4].

InSAR is a technology for monitoring Earth's surface deformations with millimeter-level accuracy. It is more cost-effective and safer than ground-based methods, while covering extensive areas. The principle is based on analyzing the phase difference of satellite images, with the result (an interferogram) displaying data on deformations, topography, and atmospheric effects [5–10].

Main objective

The aim of the study is to develop and validate an integrated methodology for monitoring Earth's surface deformations using InSAR. Special attention is given to the correction of interferogram attributes—that is, accounting for contributions from topography, atmospheric disturbances, orbital errors and structural noise. These challenges are particularly relevant for areas affected by both atmospheric and natural impacts (for instance, changes in the hydrological regime or regions undergoing intensive mining activities).

A practical application of this approach is demonstrated through a case study investigating Earth's surface deformations in the industrial zone of Kentau, Republic of Kazakhstan. This region was selected due to its complex terrain and the combined influence of mining operations and the flooding of underground workings, which lead to the development of subsidence processes, ground collapses and changes in the stress state of the rock formations. The objective is to establish an InSAR-based monitoring framework that minimizes errors associated with environmental dynamics, enabling the rapID identification of risk zones and providing a foundation for developing measures to reinforce urban infrastructure and protect the population.

The proposed integrated methodology utilizes InSAR data for monitoring Earth's surface deformations. It involves processing satellite data, eliminating distortions, and conducting time-series analysis (SBAS/PSI). The results are verified through ground-based measurements to ensure the reliability of subsidence data.

Overview of methods for modeling subsidence and deformations using InSAR

Monitoring subsidence in urbanized areas demands high precision due to dense construction and the consequent risks to infrastructure. The PSI method minimizes noise by concentrating on stable objects such as buildings and bridges. For instance, A. Ferretti et al. demonstrated the application of PSI in Milan, achieving an accuracy of up to 1 mm/year, which is critical for early risk detection. To further enhance the reliability of the results, the integration of InSAR data with GNSS is frequently employed [11]. G. M. Mullojanova and M. B. Aminzhanova [12] presented a concept for monitoring surface displacements and deformations using remote sensing data, with special emphasis on integrating InSAR with other techniques (e.g., GNSS and ground measurements) to improve accuracy and reliability. In the study by T. P. Sidiq et al. [13], the authors spatially analyzed and monitored Earth's surface subsidence in Java, Indonesia, using Sentinel-1 SAR data for the period 2017–2023. They applied the SBAS DInSAR method, corrected the data with DEMNAS and identified 10 regions with notable subsidence rates, affecting about 60 million people [13].

Deformations in industrial areas are often associated with anthropogenic loading and resource extraction. In the work by R. V. Shevchuk et al., the application of InSAR for geodynamic monitoring in the mining industry is examined. The authors analyze the capabilities of this method for detecting surface deformations caused by mineral extraction and emphasize its advantages over traditional geodetic techniques, such as high resolution and extensive area coverage [14]. The main idea of the study of D. A. Koptyakov et al. is the application of Earth's remote sensing data obtained using SAR to detect, describe, and map rapidly occurring surface deformations in the Karakechinsky deposit area. The authors analyze the methodology of processing satellite images with small perpendicular and temporal baselines, utilizing interferometric analysis of phase differences and image coherence [15]. The Small Baseline Subset (SBAS) method is effective for identifying for long-term analysis, as illustrated by M. Zhai's study of the Yuncheng coal mine, which revealed both linear and nonlinear trends in subsidence caused by industrial activity [16].

A. P. Pozdnyakov's study explores the application of InSAR technology for monitoring ground deformation in oil and gas fields. The research highlights how surface subsidence and uplift, caused by fluID extraction and injection, can be detected and measured using InSAR data. The author examines

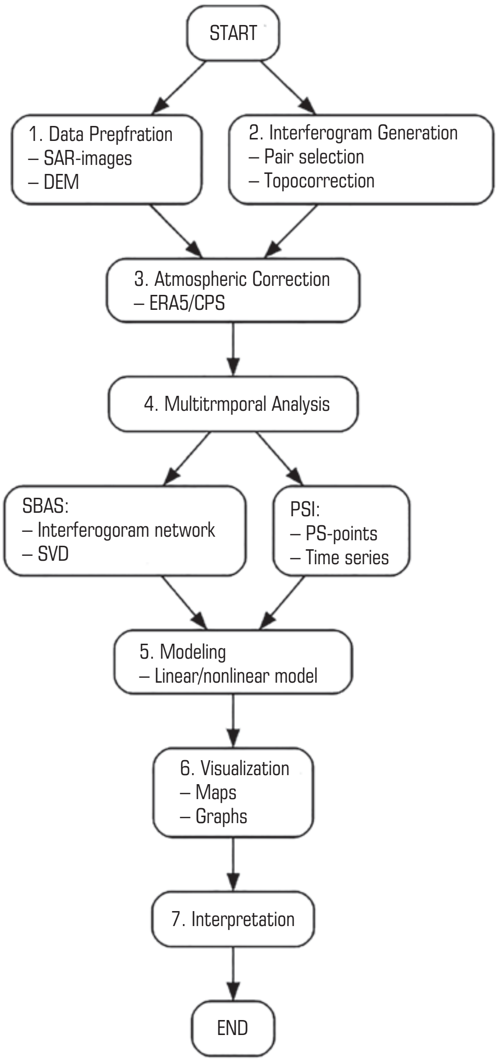

Fig. 1. Algorithm for modeling urban subsidence using InSAR

the elastic-plastic properties of geological formations and discusses the effectiveness of remote sensing in assessing structural changes within reservoirs. This approach enhances the ability to track long-term geological shifts, optimize resource extraction strategies, and mitigate environmental risks [17]. G. Zhai et al. used InSAR to track deformations related to fluID injection and achieved an accuracy of 3–5 mm/year, thereby enabling the prediction of failures and the optimization of well operations [18].

R. S. Osmanov's study explores the application of InSAR methods for determining deformation source parameters and their integration with classical surface monitoring techniques. The research examines the accuracy of remote sensing measurements, the potential for combining satellite radar interferometry with traditional geodetic methods, and its implications for geodynamic studies [19]. Deformation dynamics in quarries are characterized by rapID and heterogeneous movements. Differential InSAR has proven effective for open-pit operations; for example, L. Ge et al. detected displacements of up to 10 cm/year associated with blasting activities in Australian quarries [20]. To reduce errors in dynamic environments, Z. Perski et al. proposed a comprehensive approach that combines different InSAR techniques [21].

Recent research actively incorporates machine learning for forecasting deformations. For instance, H. Yan et al. developed a hybrID model that combines InSAR with artificial intelligence to predict subsidence with 85% accuracy by taking into account groundwater data and loading conditions [22]. The article by R. Tomás et al. is devoted to the development of a novel procedure that uses PSI data to semi-automatically identify clusters of active scatterers and perform their preliminary classification based on types of deformation zones [23]. This algorithm utilizes clustering analysis techniques adapted for processing specific InSAR signals and employs expert rules for data interpretation rather than relying on traditional sample-based learning methods (**Fig. 1**).

Modern InSAR methods (PSI, SBAS) provide high-precision deformation monitoring. For industrial sites, the key challenge is minimizing errors caused by environmental dynamics. Prospects lie in automating data processing and developing standards for interdisciplinary analysis.

1. *Input Data Preparation*. At this stage, SAR-images such as those from Sentinel-1 are obtained for a selected observation period via specialized platforms (e.g., the Copernicus Open Access Hub or the Alaska Satellite Facility). To accurately account for topographic effects, a digital terrain model (DTM) is employed, which can be derived from global models like SRTM or ALOS AW3D30. An essential prerequisite is also the integration of reference data, including meteorological information from ERA5 [24], results from GNSS-station measurements and geological maps.

2. *Generation of Interferograms*. During this stage, pairs of images are selected such that the temporal interval between them and the perpendicular baseline $B_\perp$ remain sufficiently small (e.g., $B_\perp < 200$ m and $\Delta t < 1\ year$), thereby mitigating signal decorrelation. A topographic correction is applied to eliminate the terrain contribution using the formula:

$$\Delta\varphi_{topo}\left(x,r\right)=\frac{4\pi B_\perp h}{\lambda R_1 sin\theta}, \tag{1}$$

where $B_\perp$ is the vertical (perpendicular) baseline; θ is the satellite look angle; λ is the radar wavelength; *h* is the height of the terrain; R_1 is the initial satellite-to-Earth distance.

Simultaneously, a dephasing procedure is performed to remove the contribution of the flat Earth's geometric phase. This is done using the equation:

$$\Delta\varphi_{flat}\approx\frac{4\pi B_\perp \Delta R cos\theta}{\lambda R_1}, \tag{2}$$

where ΔR represents the change in range.

3. *Correction of Atmospheric and Orbital Distortions*. The correction phase involves mitigating atmospheric distortions (through phase separation using models such as ERA5 and GNSS data) and orbital errors (vis the Precise Orbit Determination, POD method) to reduce inaccuracies.

4. *Multi-Temporal Deformation Analysis*. Here, two parallel methods are applied—SBAS and PSI. The SBAS method constructs a network of interferograms with small baselines and solves a system of equations using Singular Value Decomposition (SVD) given by:

$$\mathbf{A}\cdot\mathbf{v}=\Delta\varphi,$$

where A is the design matrix in SBAS; $\mathbf{v}$ is the vector of deformation velocities; $\Delta\varphi$ are the phase differences.

Concurrently, the PSI approach focuses on identifying stable scatterers (e.g., buildings and other urban infrastructure) and analyzing their phase time series, which further refines the deformation estimates.

5. *Modeling of Subsidence*. At this stage, subsidence modeling is carried out. In the case of a linear model, vertical displacements are calculated from the formula:

$$\varphi_{defor}=\frac{4\pi\Delta r}{\lambda}, \tag{3}$$

where Δr is the magnitude of deformation.

To account for anthropogenic factors such as groundwater pumping or additional mechanical loading on the soil typical of industrial zones

Fig. 2. Study area: The Kentau city

surrounding a city, a non-linear model is applied. In this model, deformations are approximated by the expression:

$$\Delta r(t) = a \cdot \ln(1 + b \cdot t) , \quad (4)$$

where *a* defines the amplitude or intensity of the subsidence, determining the overall scale of deformations and depending on geological conditions, soil mechanical properties, and the intensity of external impacts (e.g. groundwater extraction, surface loads); *b* influences the rate of subsidence over time. A greater value of *b* causes faster deformation at the initial stage, while smaller *b* values lead to slower and more uniform subsidence. This coefficient may also reflect the influence of accelerating factors, such as increased loading or changes in hydrogeological conditions.

Equation (4) allows for modeling the complex, non-uniform behavior of subsidence in heterogeneous substrates.

6. *Verification and Visualization*. The validation of the obtained results is carried out by comparing InSAR data with independent measurements acquired using GNSS and leveling techniques. For visualizing the distribution of deformations, modern GIS tools such as QGIS and ArcGIS are employed. Additionally, the dynamics of the subsidence are further presented as 3D models generated in software environments like Paraview or MATLAB.

7. *Interpretation of Results*. The interpretation of the results involves a comprehensive analysis of the causes of subsidence in the territory, where both geological processes and the impact of anthropogenic loads, including potential changes in groundwater levels, are examined.

Modeling subsidence in Kentau using InSAR

The city of Kentau (**Fig. 2**), situated at the foothills of the Karatau Ridge, emerged due to the development of the Mirgalimsay polymetallic deposit. Underground ore mining was conducted from 1942 to depths of up to 900 meters. Between 1994 and 2003, the mine was flooded due to unprofitability, triggering the activation of hazardous geological processes, including subsidence, sinkholes, and alterations in the hydrogeological regime. The flooding led to changes in the stress state of the rock mass, formation of fractures, and deterioration of the physical and mechanical properties of the rocks, posing risks to infrastructure and the environment. Currently, the industrial zone of the city is particularly susceptible to degradation and sinkhole phenomena.

The proposed InSAR-based algorithm is designed for the precise monitoring of deformations under conditions of complex topography and anthropogenic loading. By taking into account the unique features of Kentau, namely, its arID climate, the presence of stable reflectors (such as buildings and roads), and the dynamics of the flooded zones, the method is able to discriminate subsidence signals from background noise. The integration of SBAS and PSI techniques facilitates the analysis of both distributed and point deformations, while the correction of atmospheric distortions enhances the reliability of the results.

The application of the algorithm aims not only to retrospectively assess changes bus also to forecast risks. This capability is critically important for developing measures to stabilize the territory and to minimize damage to the population and industrial facilities.

Modeling subsidence in Kentau using InSAR involves the following steps.

1. *Input Data Preparation*. For the analysis of subsidence in Kentau, which is located near a flooded underground quarry, Sentinel-1 SAR images were acquired for the period from October 2018 to October 2020. This temporal span permits both retrospective analysis and the identification of seasonal as well as nonlinear changes in displacement dynamics.

After a detailed evaluation of the available data, it was decided to employ radar from 71 orbits, with the product polarizations being VV and VH. Subsequent parameter optimization reduced the dataset to 121 images covering the period from 2018 to 2019.

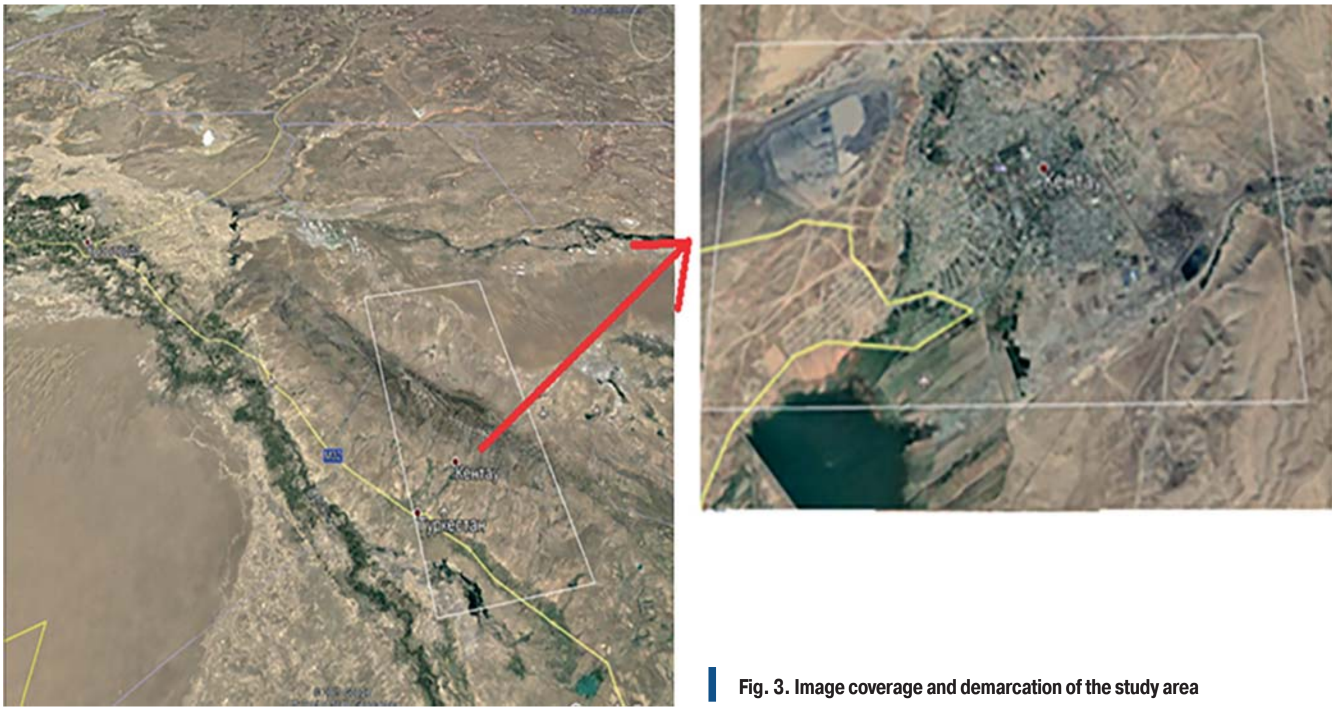

Fig. 3. Image coverage and demarcation of the study area

Initially, the processing focused on 19 SAR images from 2019 acquired between April and December 2019. These 19 Sentinel-1 images were loaded into specialized software, and the overall image coverage (**Fig. 3**) was cropped to encompass the territory of Kentau.

2. *Formation of Interferometric Pairs*. For the analysis, image pairs were selected with a temporal interval of no more than 6 months and a spatial baseline of less than 150 m. This selection criterion minimizes decorrelation effects, which is especially important for monitoring areas in close proximity to water bodies.

Topographic correction was performed taking into account local terrain characteristics, thereby adjusting the contribution of elevation differences to the interferometric phase. In other words, the topographic phase was removed from the differential interferograms using a 90 m Shuttle Radar Topography Mission (SRTM) DTM and by eliminating any orbital ramps before applying the network-flow algorithm for phase unwrapping (ISBAS).

3. *Correction of Atmospheric Effects*. Given the arID climate of the region, special emphasis was placed on correcting the dry component of the atmospheric phase using data from a local meteorological station. For areas immediately adjacent to the quarry, additional corrections were applied to account for evaporation effects from the water surface.

4. *Time Series Analysis*. At this stage, the PSI and elements of SBAS were used to determine displacement dynamics. In the urban environment of Kentau, where a high number of stable scatterers (buildings, geodetic benchmarks, anchor bolts) is observed, PSI has proven to be highly effective. The combined analysis with GNSS data, collected at a geodynamic network comprising 32 points, including a reference network of four points around the study area, yields spatial deformation maps with millimeter precision.

By convention, positive effective vertical velocities represent surface uplift, whereas negative velocities indicate ground subsidence (**Fig. 4**).

5. *Subsidence Modeling*. Data processing was carried out using GMTSAR [25] and StaMPS [26], and the visualization was performed in QGIS with the LiCSBAS plugin [27].

The processed data indicates that deformations in the central part of the city are minimal, while moderate subsidence is evident in residential areas. Overall, the analysis of displacements throughout Kentau has highlighted critical zones where subsidence occurs at an average annual rate of up to -12 mm/year, alongside areas exhibiting local uplift of up to +7 mm/year (see Fig. 4). These findings are particularly significant for the assessment of structural stability and for developing recommendations for further monitoring.

6. *Verification of Results*. Verification based on GNSS and InSAR data for the period from November 2019 to March 2020 shows overall agreement in trends between the two methods, although some local discrepancies are evident (**Fig. 5**). In the majority of observation points, negative displacement values were recorded, confirming the presence of subsidence processes. The greatest mismatches between the methods were observed at points within zones of active deformation. Thus, the integration of GNSS and InSAR data proves particularly effective in areas experiencing active tectonic processes, providing a more comprehensive depiction of the nature and scale of ground surface deformations.

7. *Interpretation and Recommendations*. The proposed methodology, utilizing SBAS and PSI techniques, has enabled the identification of various types of surface deformations in the industrial zone and the city of Kentau, including:

—subsidence,
—suffusion-karst processes,
—surface shifts and building deformations,
—restoration of the hydrological regime,
—local flooding of residential and industrial areas.

In conclusion, for effective monitoring of the study area's surface, an annual area-wide surveillance program using radar interferometry combined with ground-based measurements is recommended. Ground-based instrumentation should be deployed at potentially dangerous locations identified through the processing of the acquired radar images. Based on these results, it is advisable to establish geodynamic monitoring (GMD) on a unified methodological basis, thereby ensuring the timely protection of the buildings and structures in the city of Kentau.

Conclusions

As a result of the work undertaken, an integrated methodology for monitoring urban surface deformations using InSAR has been developed. The study demonstrates that the sequential processing of data, which encompasses the preliminary preparation of input information, interferogram generation, correction of atmospheric and orbital distortions, as well as multi-temporal deformation analysis, enables the production of spatio-temporal maps of vertical displacements.

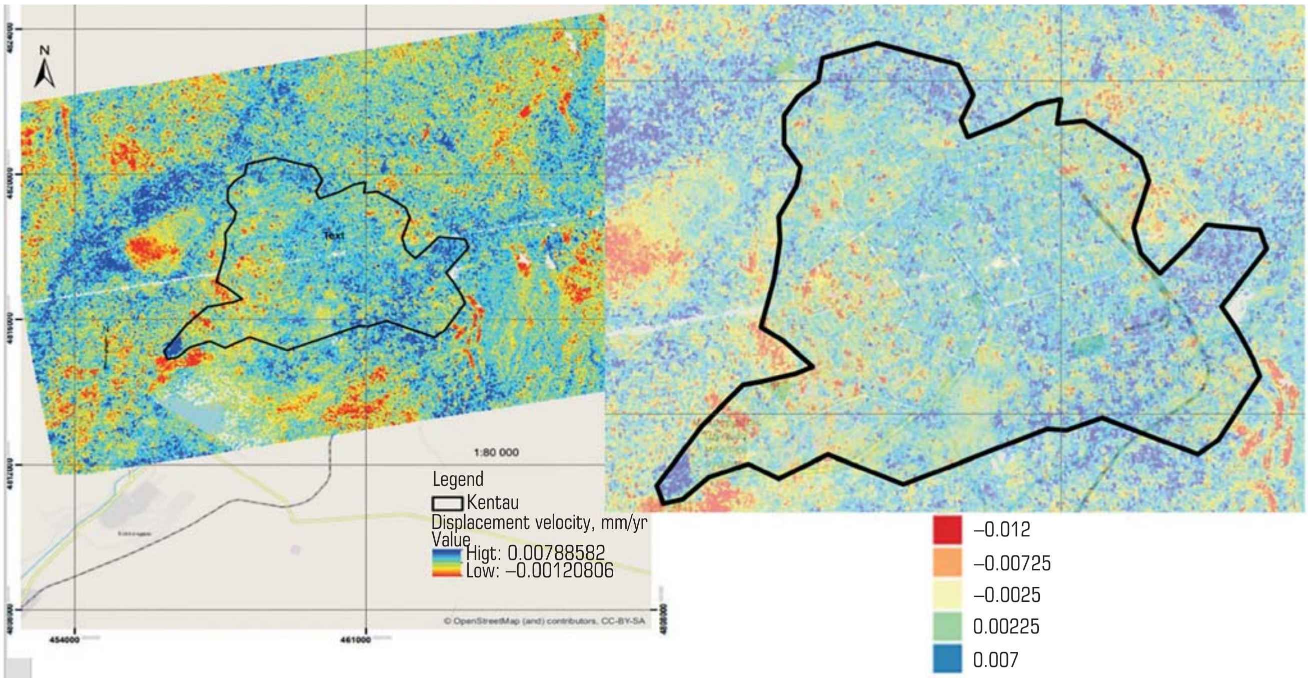

Fig. 4. Displacement map obtained using the control ISBAS method [25]

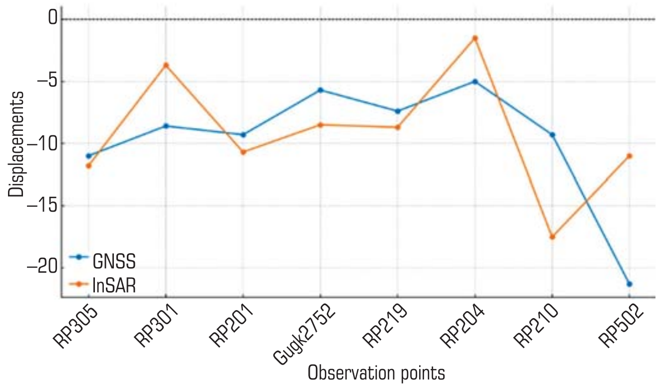

Fig. 5. Comparison of GNSS and InSAR

The investigation of ground surface deformations in the industrial zone of Kentau, based on InSAR methods, has significantly contributed to understanding the scale and dynamics of environmental risks associated with the flooding of the Mirgalimsay ore deposit. The obtained data revealed zones of intense ground subsidence (up to 25 mm/year) along with an intensification of collapse processes, thereby confirming the critical condition of the region's infrastructure and ecosystem. These findings have emerged as one of the key arguments for the official designation of the territory as an emergency zone until 2075, as specified in the governmental decision [28].

Moreover, the use of SBAS and PSI technologies has not only allowed for a quantitative assessment of deformations but also enabled the forecasting of their future evolution, which is indispensable for devising long-term stabilization measures. Continued monitoring using InSAR remains a pivotal tool for minimizing the adverse effects of flooding and ensuring public safety.

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INCLUSION OF SALT ROCK JOINTING IN EVALUATION OF LOAD-BEARING CAPACITY OF RIB PILLARS

The study assesses the effect of including the decrease in elastic properties of salt rocks in calculation of the bearing capacity of different-size rib pillars under varying effective pressure. Based on the review of domestic and foreign reference sources, we selected the correlation between the change in the uniaxial compression strength and the decrease in Young's modulus. A modification of the approach to estimation of loading of rib pillars is proposed. It is based on the mathematical modeling of normalized stress intensity at the central point of a pillar. In this article, this calculation model is implemented as a case-study of productive sylvinite stratum Kr II at the Verkhnekamskoe (Upper Kama) salt deposit. The approximation relationships for the decrease in elastic properties with an increase in maximum effective stress are based on the results of laboratory experiments on step-by-step uniaxial compression of sylvinite specimens. Based on the results of computational experiments, we find that the dependence of elastic properties of sylvinite on maximum principal stress has the most significant impact on the load-bearing capacity of pillars with width-to height ratios of no more than 1 at the effective pressure of total undermining. For instance, the maximum change in the degree of loading of the rib pillar is 26%, from 0.5 to 0.63, and this occurs for a pillar with a shape factor of 0.75.

Keywords: *Room-and-pillar mining system, pillar stability, Verkhnekamskoe Salt Deposit, mathematical modeling, fracturing, elastic moduli*
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Introduction

One of the widespread methods of underground mining is the room-and-pillar mining system. This system provides maintenance of overlying strata by load-bearing elements of various sizes [1–4]. Mining operations are carried out at the Verkhnekamskoe (Upper Kama) salt deposit (VKSD) with some productive rocks left in the form of rib pillars supporting the overlying rock strata. The stability of the rib pillars directly relates to the safety of the water-protective layer that separates the aquifer from the mined-out space of the mine. A breach in the continuity of the water-protective layer leads to the breakthrough of fresh water into the mine workings, to intense dissolution of salt rocks and to ultimately flooding of the mine with enormous socio-economic consequences.

In accordance with current regulatory documents [5, 6], the calculation of the loading degree of rib pillars at VKSD is based on the Turner–Shevyakov method [7, 8]. According to this method, the loading degree is determined by the ratio of the load acting on a pillar to its bearing capacity. In this case, the load on a pillar is determined by the weight of rock mass above it, and the bearing capacity depends on the shape of the pillar, the strength of the rocks, and several other geological factors that are specific to the deposit: