# Improvement of the Monitoring Methodology Using Space Images in the Tasks of Assessing Tailings Dam Subsidence

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**Abstract**

Maintaining the operational strength of containment dams and hydraulic structures, while increasing the storage capacity of existing TSFs, is a relevant task to ensure the stability and environmental safety of areas located near the tailings storage facilities.
During the operation and reclamation of hydraulically deposited mining and technical masses (hydraulic dumps and tailings storage facilities), significant importance is attached to issues related to geomechanical processes, which largely determine the stability and environmental safety of the structure, its capacity, and the direction of its further use. Therefore, methodologies are being developed for the operation of TSFs and the improvement of their monitoring, including the creation of a scientific and technical base.
Despite the improvement of methods for assessing and calculating stability, the emergence of powerful computing technologies and corresponding software, as well as the expansion of controlled parameters of TSFs, the monitoring and management of the stability of tailings dams remains one of the most pressing problems of industrial hydraulic engineering.
This paper examines the issues of improving the monitoring of TSF dams of the Almalyk Mining and Metallurgical Combine Concentration Plant (MCC). The purpose of the research is to increase the operational safety and predict the condition of the containment dams of TSFs based on the use of satellite radar interferometry (InSAR) and the improvement of the methodology for instrumental mine surveying observations to prevent hazardous deformations.
Sentinel-1 synthetic aperture radar data of open access provided by the European Space Agency, as well as mine surveying data of the territory, were selected as the initial data for the research.

## 1. Introduction

Tailings storage facilities are constructed for the purpose of receiving slurry (a mixture of production waste with water) discharged from processing plants, separating the solid phase of the beneficiation waste from the hydromixture, and its storage (Besimbaeva O.G., 2010). The dams and embankments of waste storage facilities of mining and processing plants are among the most critical hydraulic structures (Yakovlev V.N., 2002). They must be not only statically and filtrationally stable, but also meet the requirements of environmental protection. Leakage of wastewater from the storage facility is not permitted without appropriate mechanical, chemical, and biological treatment; discharge beyond the boundaries of the storage facility is prohibited. As a result, these structures are subject to risks of internal erosion, settlement, filtration, flooding, and seismic impacts, which require continuous monitoring.
Practice (Kosikov E. M., 1997) shows that accidents at hydraulically deposited structures are caused in 40% of cases by insufficient and incorrect engineering and geological investigations, in 30% — by incorrect choice of technology during the design of the structures, and in 25% — by violations of the operation technology of the facilities (Kirichenko Yu. V., 2001).
Analyzing the existing methods of calculating the stability of slopes of man-made structures, it should be noted that, to date, sufficiently reliable calculation schemes have been developed corresponding to various hydrogeological and technological conditions of their operation. However, the main focus in these methods is on the stability of the dam slope itself, and the influence of gravitational and filtration forces. At the same time, the issues of monitoring the stability of dams and the dam body along the foundation, taking into account time-dependent changes in the physical and mechanical properties of the dam body soils and their foundation, geometric parameters of the structure, and the stress-strain state of the dam, which leads to significant displacements of containment dams and, consequently, to a decrease in the stability of the tailings storage facilities, have not been sufficiently studied. It is precisely in this direction that further research should be continued.
Timely anti-deformation measures aimed at preventing violations of the integrity of the slopes of containment dams, carried out on the basis of mine surveying observations and dam stability calculations, ensure the safety and environmental equilibrium of the regions where they are located.
For in-depth study and analysis of this technogenic problem, long-term comprehensive observations of the stability condition of tailings dam structures are being conducted in Uzbekistan. These comprehensive observations include several traditional ground-based methods: gravimetric studies for monitoring the compaction of the formation; GNSS and high-precision leveling surveys for mapping ground deformation; and seismological studies for monitoring the frequency and distribution of natural and anthropogenically induced seismicity (Kouznetsov, O. and others, 1994).

## 2. Methodology

At present, on the sites of the combined tailings storage facility of the Concentration Plant No. 2, regular and reliable control over the stability condition is carried out using traditional methods, which include mine surveying observations of vertical and horizontal displacements of the dam body. The main purpose of these activities is the timely detection of hazardous geodynamic processes that may lead to the loss of dam stability. Based on these data, the level of dam stability is assessed and the most probable deformation zones are identified, which allows for the accurate determination of the locations of measuring instruments and observation points.

Currently, the monitoring of deformation processes over large areas is generally carried out using traditional mine surveying and geodetic methods, such as high-precision leveling and high-precision satellite observations. It should be noted that although these methods are considered standard references, they require significant financial and time resources. In addition, the efficiency of obtaining information based on these methods is relatively low, as acquiring data on the dynamics of deformation processes requires conducting continuous series of observations and constant post-processing of the results (Musikhin, V. V., 2012).

Along with traditional monitoring methods, many countries around the world have implemented large-scale scientific research and practical systems aimed at the control of mining and metallurgical industry waste.

In recent years, geoinformation technologies (GIT), remote sensing (RS), unmanned aerial vehicles (UAVs), digital elevation models (DEMs), and global navigation satellite systems (GNSS) have become promising alternatives and supplements to traditional mine surveying monitoring. The capabilities of these technologies make it possible to determine the spatio-temporal dynamics of waste spread, model risk zones, develop real-time early warning systems, and visualize monitoring results in an interactive format. The use of modern remote sensing technologies in areas such as geotechnical risk, environmental monitoring, and remote management of industrial waste has brought fundamental changes to the industry.

In light of the above, many researchers have begun actively implementing new methods for monitoring deformations of large territories, among which the method of satellite radar interferometry has shown exceptional development in recent years (Musikhin, V. V., 2012). With the advancement of space technologies, the use of satellite data in Earth sciences has marked the beginning of the development of remote sensing. Satellite imagery has opened up new prospects for monitoring changes occurring on the Earth's surface. As a result, the process of creating maps of land and water resources, monitoring the environment, including geodynamic processes of technogenic origin, has become significantly simplified (Orynbasarova, E. and others, 2024).

SAR instruments can be mounted on-board aircraft or satellite platforms; they work by transmitting microwave pulses toward the Earth surface and by measuring the microwave echoes scattered back to the sensor platform. SAR is an imaging system with all-weather, day and night sensing capability that nowadays plays a key role for the remote sensing of the environment, and in particular it is extensively used for the monitoring and analysis of several geophysical phenomena (Solaro G. and others, 2016).

One of the major applications of the SAR technology is represented by the SAR interferometry (InSAR) technique, which is based on the measurements of the phase pattern difference between two complex-valued SAR images acquired from two different orbital positions, and allows the measurements of geomorphological characteristics of the ground, such as the topography height and its modifications over time (e.g., the surface deformation) due to earthquakes, volcano eruptions, or other geophysical phenomena. Historically, the main application of InSAR was the retrieval of the terrain topography [4–6]. Depending on the time when SAR acquisitions are collected and the orbital position of the SAR platform, different InSAR configurations can be distinguished. Cross-track interferometry is a basic SAR interferometric configuration in which two antennas are arranged across the track of the platform, as sketched in Figure 1.

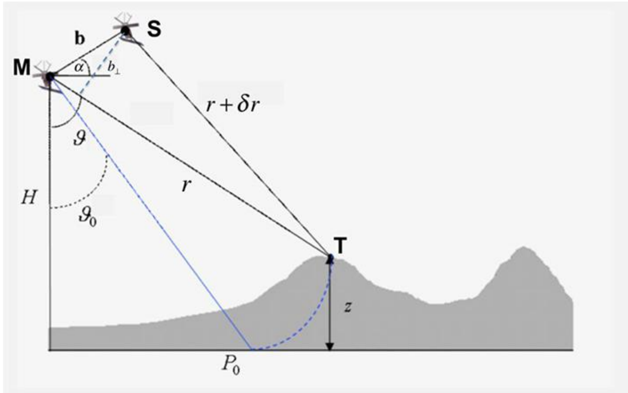


Figure 1. SAR interferometric configuration. The black lines show radar signal paths for an interferogram pair formed by the antennas M and S.

Differential SAR interferometry methodology has first been applied to investigate single deformation events. At the present days, however, it is chiefly applied for the computation of displacement time-series through the so-called multitemporal (or multichannel) interferometric SAR approaches (Solaro G. and others, 2016). At present, in many countries of the world, radar data are actively used for monitoring purposes; however, in countries such as Italy, the United Kingdom, the Netherlands, the USA, Germany, Japan, and Switzerland, progressive development and modification of the methodology for analyzing and interpreting radar data is taking place (Orynbasarova, E. and others, 2024). International experience shows that the integration of satellite radar interferometry technologies is an important tool for monitoring, assessing, and managing risks associated with tailings storage facilities (3D Visualization Monitoring, 2022; Rauhala A., 2017).

This technology not only provides wide spatial and temporal coverage but also allows modeling of monitoring results in a digital environment, performing automated analysis, forecasting, and integration with management systems. At the same time, the implementation of such systems requires a preliminary technological base, the availability of highly qualified specialists, and financial resources.

The mass use of radar data over the last four years has become possible with the appearance of freely accessible Sentinel-1 radar data.

The results of radar interferometry can provide information on the history of vertical displacements at points on the Earth's surface. If the data are correctly interpreted, it is thus possible to obtain information on changes in settlement rates at specific points.

Such information can serve as a basis for short-term forecasting of settlement processes, based on the dynamics of settlement rate changes (Musikhin, V. V., 2012). The main distinguishing features of high-resolution radar data from new-generation satellites are their spatial resolution up to 1 meter, the ability to perform imaging with different polarizations, and subsequent interferometric processing to obtain high-precision digital elevation models and detect surface displacements.

The principle of determining surface settlement is based on the phase difference between two cycles of radar imaging at a specific point. The phase difference of the two imaging cycles will be zero if no surface movement has occurred, and non-zero if displacement has taken place at the observed point (Merkel and others, 2023).

Let us consider again the imaging geometry depicted in Figure 1, where the first SAR image (i.e., the master image) is taken from the orbital position labeled to as M, and the second one (i.e., the slave image) is captured from the orbital position labeled to as S, at a distance b (typically referred to as baseline) from M. Taking into account simple geometrical considerations relevant to the considered geometry, it is possible to uniquely locate each imaged targets on the ground and get an estimate of their heights (namely, z) above the reference plane. As evident by inspection of Figure 1, if a same target (namely, T) is observed from two orbital positions (master and slave), the difference between the path lengths to the target can be correctly measured and the target height z above the assumed zero-altitude plane can be unambiguously determined. This is obtained by taking into account the following two equations (see Figure 1):

$$(r+\delta r)2=r2+b2-2rb\sin(\vartheta-\alpha) \tag{1}$$

$$z=H-r\cos\vartheta \tag{2}$$

where $\delta r$ and $\delta + \delta r$ represent the radar ranges from the corresponding antennas to the target point being observed, $\vartheta$ is the radar look angle, $\alpha$ represents the angle of the baseline relative to the horizontal, $z$ denotes the scatterer height above the flat-earth reference, $H$ is the height of the sensor above the reference surface, and b is the physical separation of the antennas that is referred to as the baseline of the interferometer. Notice that (1) derives from the application of the cosine rule to the *MST* triangle and (2) is a simple geometric relationship linking the target topography (z), the sensor height (H), and the radar side-looking angle (ϑ). The ability in successfully reconstructing the unknown topography (z) is strictly dependent on the capability to precisely measure the slant-range difference δr, which represents one of the known terms of the system of Eqs. (1) and (2) (Solaro G. and others, 2016).

In practice, the implementation of this process for determining surface settlement is associated with errors caused by several factors that significantly reduce data quality. The quality of the resulting interferogram is affected by errors contained in the original scenes and errors related to the joint processing of the two scenes used to create the interferogram (Musikhin, V. V., 2012).

Based on the method of obtaining the information contained in the scenes, and the temporal separation of the interferometric imaging processes, one can identify the factors accompanying the process of obtaining scenes through radar imaging — both at the moment of direct data acquisition by the satellite and at the moment of radar data processing (Musikhin, V. V., 2012; Orynbasarova, E. and others, 2024). The main driver for the development of PSI technologies was the need to overcome the errors introduced into signal phase values by atmospheric artifacts. By examining multiple images, many interferograms are generated by selecting one of the scenes as a master to which the other scenes become slaves. Statistically-based tests are then conducted on all of the interferograms to identify, quantify and remove the atmospheric component. Having removed the atmospheric artifacts, the data that remain are upward and downward displacement values plus noise, which cannot be removed.

Errors in interferograms (during joint processing of scenes) arise from the combination of errors present in the individual scenes and errors of their joint processing. The phase at a point in the differential interferogram will be changed relative to the phase in the original interferogram by the amount of corrections introduced due to the effects of terrain, baseline, atmospheric influence, and noise (3):

$$\Phi = \Phi_{topo} + \Phi_{def} + \Phi_{atm} + \Phi_{n}, \tag{3}$$

where: $\Phi_{topo}$ – topographic component;
$\Phi_{def}$ – phase difference caused by surface displacements during the time interval between acquisitions;
$\Phi_{atm}$ – atmospheric disturbance;
$\Phi_{n}$ – electromagnetic noise.

Despite the apparently consistent patterns resulted from processing of satellite images, the method InSAR is only used as a supplemental technique since the relevant regulatory framework is yet absent. In combination with the conventional surveying for monitoring ground surface deformations, the method InSAR enhances efficiency of monitoring and improves accuracy of geodynamic risk prediction in the course of mineral mining, inclusive of observations over the global tectonic processes. The probabilistic kinematic analysis allows for getting insight into the mechanism of overlying rock mass movement with regard to rock mass jointing and, jointly with InSAR, can be used in the artificial intelligence systems for learning models of prediction of overlying rock movement parameters during mineral mining (Sergunin M. P., 2022).

## 3. Results and Discussion

In the territory of our Republic, the use of radar data for solving surface displacement monitoring tasks is gaining increasing popularity (Rakhimova M. Kh., 2024). As a result of interferometric processing of radar data from Sentinel-1 satellites, independent remote sensing data were obtained (Figures 2, 3). Currently, the processing of these data using software tools and the identification of the deformation state of the area are ongoing.


Figure 2. Identification of the location of the study area based on satellite imagery

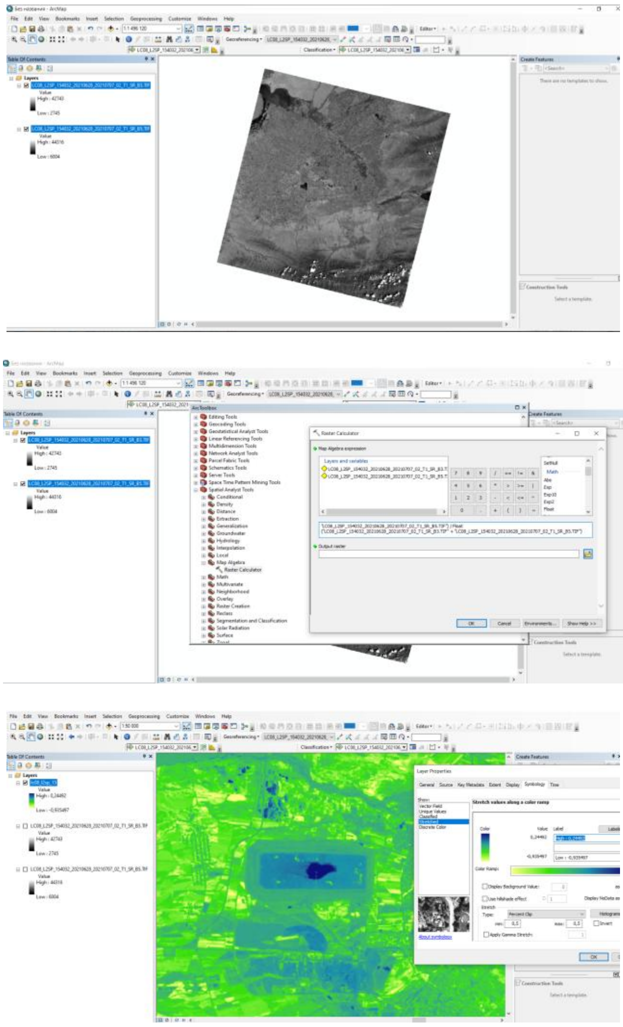

Figure 3. Processing of satellite imagery data

In the area observed by the radar interferometry method, traditional mine surveying measurements were also simultaneously carried out (Figure 4). The combination of various geodetic methods requires an observation network that is accessible for each of the used methods. The planning, selection, and installation of measurement points were carefully carried out. Similarly, on the selected section of the tailings storage facility at the copper concentration plant of the Almalyk Mining and Metallurgical Combine (AMMC), namely the northeastern section of the dam, an observation station was established. The northern side of the tailings dam is the most hazardous in terms of potential dam failure for the adjacent built-up areas, which are located hypsometrically below the elevation level of the tailings storage facility (Sajjidkosimov, S. S. and others, 2023).

To determine the stability of the position and condition of the dam of the combined tailings storage facility, observations were conducted using both satellite technologies and classical methods (Rakhimova M.Kh. and others, 2020). The observations were performed using traditional methods (Class III leveling based on GPS points) as well as by means of satellite positioning. The satellite measurements were carried out using the static method.


Figure 4. Layout of working benchmarks located on the dam and the adjacent area

The coordinates of the working benchmarks in all cycles were calculated in a local coordinate system. The coordinates of the points were determined using the Credo_Dat 4 software. Additionally, for control and analysis purposes, the coordinates of the points were also determined using classical methods (Mirmakhmudov E.R. and others, 2021). As a result, horizontal and vertical displacements of the benchmarks were identified based on the results of traditional methods (Figure 5).

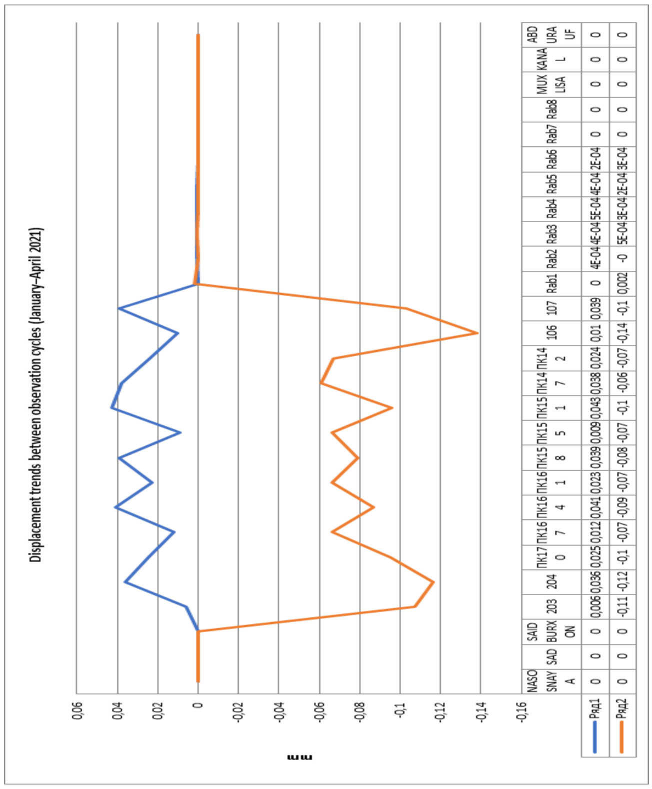


Figure 5. Displacement graphs between cycles: Series 1 – horizontal displacements, Series 2 – vertical displacements

Based on periodic instrumental observations (2 series) of horizontal and vertical displacements of benchmarks using modern electronic instruments, hazardous zones were identified where preventive and anti-deformation measures must be undertaken to ensure the stability of the dams (Rahimova, M. and others, 2024).

Based on the conducted observations, as well as the mathematical processing and analysis of their results, it was


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established that deformation processes at the tailings storage facility sites are ongoing (Sajjidkosimov, S. S. and others, 2023). The average displacement values for this period were as follows:

| Zone | Horizontal Displacement, mm | Vertical Displacement, mm |
|---|---|---|
| Southeastern part | 32.3 | 124.0 |
| Dam body | 47.9 | 123.6 |
| Northwestern part | 20.4 | 51.9 |

The displacement rates since the beginning of the observations were as follows:

| Zone | Horizontal Displacement, mm/month | Vertical Displacement, mm/month |
|---|---|---|
| Southeastern part | 1.36 | 5.23 |
| Dam body | 2.02 | 5.22 |
| Northwestern part | 0.86 | 2.19 |

Maximum displacement values:

| Zone | Benchmark | Horizontal Displacement, mm | Vertical Displacement, mm |
|---|---|---|---|
| Southeastern part | Rp0104 | 54.0 | — |
| | Rp0202 | — | –291.0 |
| Dam body | Rp0203 | 151.7 | 383.1 |
| Northwestern part | Rp0109 | 28.5 | — |
| | Rp0208 | — | –67.5 |

It should be noted that the displacement rates are within the following ranges:

Horizontal – from 0.86 to 2.02 mm/month

Vertical – from 2.19 to 5.23 mm/month

Displacements in the northwestern part (agricultural land) are insignificant and range from 0.03 to 0.07 mm/day.

For the other two areas, vertical displacements amount to 0.17 mm/day.

In addition, the settlements at benchmarks 0107 and 0207 are of approximately the same order, ±4 mm, which is within the measurement accuracy. This confirms the reliability of the measurement results.

According to the results of observations, the average settlement rates based on GNSS data are 5.2 mm/month and 4.8 mm/month.

## 4. Conclusions

At present, the radar interferometry method is not yet a fully universal tool in the field of geodynamic monitoring — it cannot completely replace traditional monitoring methods and has specific features and limitations that must be taken into account when determining ground subsidence.

There are well-known challenges in determining absolute subsidence values in zones of intensive deformation processes (phase unwrapping), especially under conditions of low data correlation.

Classical methods of spatial phase unwrapping allow for an objective assessment of subsidence; however, they provide reliable results only under conditions of short time intervals between multiple satellite passes and high data correlation.

Thus, interferometric analysis of the deposit area provides important and practical results regarding the activity of deformations and their spatial distribution. This opens up opportunities for real-time monitoring of deformation processes across large areas.

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