Interdisciplinary Studies and Digital Technologies in Monitoring Liquid Mining Waste Reservoirs of the Barents Euro-Arctic Region

Anatolii Kalashnik[a]
Mining Institute Kola Science Centre RAS, 184210, Fersman st.24, Apatity, Russia
a.kalashnik@ksc.ru

Keywords: Interdisciplinary Studies, Digital Technologies, Monitoring, Combination of Methods, Liquid Mining Waste Reservoir, the Barents Euro-Arctic Region.

Abstract: The paper demonstrates the relevance of diagnostics and monitoring of liquid mining waste reservoirs located at the Barents Euro-Arctic region and designated as especially responsible objects (I-II hazard class). The author has developed the methodological basic principles of interdisciplinary methods application for combined observations and studies in a monitoring system: hydraulic engineering, hydrogeology, geomechanics, geodesy, geophysics, GPS geodesy, aerial photography, the Earth's remote sensing (ERS), geoinformatics, computer modeling, and digital technologies. The combined in-situ observations are carried out at four levels correlated with the Earth's surface: satellite, aerial, surface and subsurface (underground).The satellite level includes GPS geodesy, processing and analysis of optical, spectral and radar images (ERS). The aerial level deals with different digital aerial photographies. The surface level is based on robotic geodetic measurements, laser and radar scanning of objects' surface and relief. The underground level includes hydrological measurements, seismic tomography and GPR sounding. On the basis of the obtained in-situ results, hydrogeomechanical 3D models are designed and filtration-deformation processes are simulated in a scenario.Such approach in different combination of interdisciplinary studies, both on the same and different levels, makes it possible to solve monitoring tasks in a hierarchy from a liquid mining waste reservoir as an object as a whole (tens of square kilometers) to individual components (kilometers and hundred meters) and local sectors (meters and fractions of meters). The paper gives experience of implementation of interdisciplinary studiesand digital technologies in monitoring of liquid mining waste reservoirs owned by principal mining companies located at the Barents Euro-Arctic region.

1 INTRODUCTION

The destruction of tailings dams of mining enterprises, as well as negative incidents and major catastrophs of liquid mining waste reservoirs (Aika, Hungary; Brumadinho, Brazil; Ind, Pakistan, etc.), which led to the death of people and enormous socio-economic losses, make the need for continuous monitoring and diagnostics of the state of liquid industrial waste reservoirs a top priority (Carmo et al, 2017; Kalashnik, 2020; Kulikova, 2022; Tailings info, 2018; World Mine, 2018; Zongjie, 2019; 11 of the world's, 2017).

An example of a large-scale disaster is the accident at the liquid waste reservoir of the Ajka Timfoldgyar Zrt aluminium plant near Ajka town, Hungary, on October 4, 2010 (World Mine, 2018; 11 of the world's, 2017). As it turned out after the accident, the tailings dam was in an emergency condition, and the tailing dump was as full as possible. As a consequence, the tailings dam collapsed, and red sludge with toxic waste leaked out.

Post-accident surveys found that approximately 1.1 million m^3 of toxic waste was released into the environment, and the area of the spillage was about 440,000 m^2. Seven people died, and about 150 people suffered from poisoning and chemical burns. The spillage of contaminated water destroyed 300 homes, and about 800 residents of Aika town were evacuated (Tailings info, 2018).

A violation of filtration and functionality, loss of stability of tailings dams ofliquid waste reservoirs lead to an emergency situation, the consequence of which is considerable social and economic damage to the population, civil and industrial buildings, roads,

[a] https://orcid.org/0000-0001-6567-2877

utilities, etc. An accident entails financial losses (lost profits due to the shutdown of the enterprise), additional costs (repair and restoration works on dams, roads, power lines, devices and mechanisms, etc.; liquidation of the accident consequences; restoration of the surrounding natural systems), as well as fines for environmental pollution and environmental damage (Kalashnik, 2020; Kovlekov, 2021; Zongjie, 2019).

Mineral ore is extracted and processed in the Barents Euro-Arctic region by major mining companies such as Kola MMC (Pechenganickel), Kovdorsky GOK, Kirovsk Branch (KB) of Apatit, OLCON, NWPC, and Lovozersky GOK.

To date, these enterprises extract a total of 60-80 million tons of ore per year, which is processed at dressing plants into the final product - mineral concentrate, and the processing wastes (the total annual volume of 40-50 million tons) are dumped by the dressing plants in specially constructed for this purposeliquid mining waste reservoirs. It should be noted that the tailings dumps of the dressing plants in the Western part of the Russian Arctic sector are built in ravines or river (stream) hollows, on relatively weak soils of the underlying geological base (Kalashnik, 2020).

Intensive subsoil use for almost 90 years in the Barents Euro-Arctic region has resulted in constructing large tailings dumps, which contain more than 1 billion m^3 of processing waste, with a total weight of about 2.43 billion tons. According to the Mining Institute KSC RAS data, three tailing dumps of KB Apatit have accumulated more than 1 billion tons of tailings, with a total volume of almost 500 million m^3; Kola MMC JSC - about 500 million tons (over 220 million m^3); OLCON JSC - a little less than 500 million tons (210 million m^3); and Kovdorsky GOK - about 370 million tons (160 million m^3).The area of the tailings dums may reach 16.5 mln m^2 (1,650 ha), with the volume of the filled cup more than 318 mln m^3 (318.4*109 litres), and the weight of the total mass of the tailings deposits up to 732 mln tons. The height of tailings dams reaches 70m, which is almost 5 times higher than the height of a 5-storey building. The region’s tailings dumps belong to the category of especially responsible (hazardous) objects; hazard class I-II.

Thus, the tailing dumps of mining enterprises in the western part of the Russian Arctic sector are huge reservoirs of liquid mining waste; they are open dynamic natural-engineering systems, closely linked with the natural environment.In the areas where tailings dumps are located, there is a significant degradation of the natural environment and changes in the hydrogeological regime, including surface water bodies and groundwater. Taking into account the annual growth of waste volumes over 40 million tons, these transformations are continuing and increasingly determine the necessity and urgency of the task to control the conditions of tailings dumps and forecast the tendencies of environmental changes (Kalashnik, 2020; Kovlekov, 2021).

Special attention should be paid to the hydrogeological regime of the location of tailings dumps, which, due to both the high level of natural groundwater and the permanent water-saturated slurry storage of tailings from dressing plants, is constantly and significantly changing (Kovlekov, 2021; Tikhonova, 2021).

First of all, it leads to the formation of increased pore water pressure in the soils of all hydraulic facilities of the tailings dump. As a result, the effective stress in the soils is low, and for reliable operation of the tailings dump and to ensure the mechanical and filtration stability of the tailings dams, time periods must be taken during which intermediate compaction of soils occurs due to their consolidation (Kalashnik, 2020; World Mine, 2018). Due to consolidationand soil compaction, excessive pore water pressure is dissipated and reduced, and the soil can acquire a "skeletal" stiffness that provides the shear strength necessary for the operation of the dam (Clarkson, 2020; Kalashnik, 2020; Kovlekov, 2021; Tailings info, 2018).

The above, as well as the negative experience of the dam failures that resulted in the death of people and enormous socio-economic losses, make it necessary to constantly monitor and diagnose the hydrogeomechanical condition of tailings dumps as reservoirs of liquid mining wastes (Clarkson, 2020; Kalashnik, 2020; Tailings info, 2018; World Mine, 2018; Zongjie, 2019; 11 of the world's, 2017). In this case, the main problem of control and diagnostics is that the dangerous filtration-deformation processes occur in the subsurface weakened and heterogeneous soils, initially hidden from visual and ground observations.Such processes can be registered at an early stage only if applyingdifferent-scaleand different-levelinterdisciplinary methods, which allow controlling both the tailings dump as a whole, and the associated natural-engineering systems (Clarkson, 2020; Kalashnik, 2020).

The purpose of this work is to justify the use of interdisciplinary studies and digital technologies in monitoring liquid mining waste reservoirs, and optimize their combination in order to solve specific monitoring tasksin the Euro-arctic conditions.

2 METHODS

The main idea was to involve interdisciplinary studies and digital technologies for in-situ observations and computer modeling of a liquid mining waste reservoir as a particularly responsible object of hazard class I. The author proposes to use interdisciplinary methods and digital technologies, both in the in-situ observations and in the processing, interpretation and analysis of the obtained multi-format data (Figure 1).This approach allows implementing a rapid diagnosis, assessing the state of the reservoir, timely detecting deterioration of reliability and functionality and providing operational control over the development of potentially dangerous filtration-deformation processes.

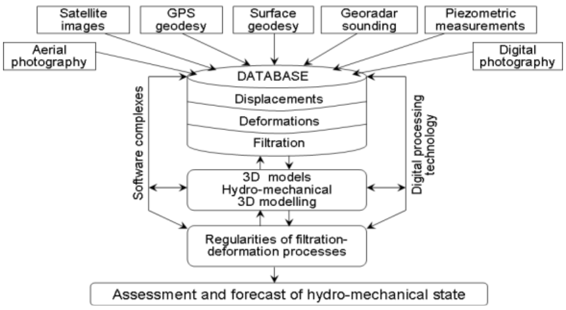

Figure 1: Methodical approach to monitoring the liquid mining waste reservoir based on interdisciplinary observation methods and digital technologies.

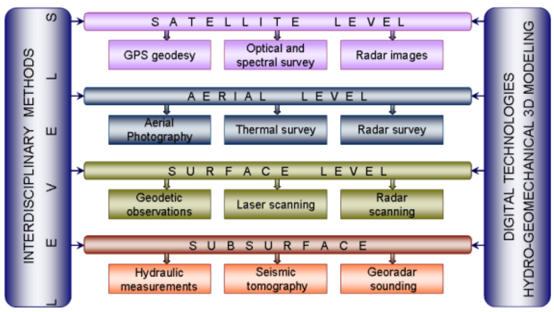

Figure 2: Concept of multilevel application of interdisciplinary studies for monitoring the liquid mining waste reservoir.

For this purpose the author developed the concept of application of interdisciplinary observation methods at different levels (in relation to the day surface) in monitoring of the liquid mining waste reservoir (Kalashnik et ai., 2022) (Figure 2).

The concept includes, on the one hand, available modern control and diagnostics methods for the liquid mining waste reservoirs as open dynamic natural-engineering systems, and is focused, on the other hand, on diagnostics of the hydro-geomechanical state of the reservoirs and detection of potentially dangerous filtration-deformation processes at early stages (Kalashnik, 2020; Melnikov et al., 2018).

Tailings monitoring is implemented with interdisciplinary observations and different levels such as satellite (GPS geodesy, optical, spectral and radar spacecraft imagery (Alabyan et al., 2016; Antonov, 2021; Hartwig, 2016; Kalabin et al., 2016; Kalashnik, 2020; Mikhailov et al., 2016; Morin, 2016; Melnikov et al., 2018; Napolskikh et al., 2017; Ponomarenko et al., 2020; Rybnikov and Buzina, 2021; Sashurin and Panzhin, 2020; Tikhonova, 2021)), aerial (various aerial UAV photography (Kalashnik, 2020; Melnikov et al., 2018)), surface (visual observations, photo-fixation, geodetic surveys and measurements, laser and radar surface scanning (Kalashnik, 2020; Kuchinskaya and Stavskaya, 2021; Maksimov, 2021; Maksimov and Dyakov, 2021)), and underground (hydrological measurements, piezometer and borehole groundwater level recordings, seismic tomography, georadar subsurface scanning (Kalashnik, 2020; Melnikov, et al., 2016; Musalev et al., 2018)).This makes it possible to solve multiscale monitoring tasks: from local sectors and components (from millimeters to meters) to the reservoir as a whole (from hundreds of meters to tens of kilometers). An important addition to the interdisciplinary methods of in-situ observations are digital technologies: construction of 3D models and hydro-geomechanical 3D modeling, as well as the use of BIGDATA and CLOUDSERVICE processing technologies (Bahkaeva and Guriev, 2016; Deryabin and Misineva, 2022; Kalashnik, 2019; Zinovieva et al., 2021).

The application and direct relationship of interdisciplinary methods and digital technologies in the monitoring of the liquid mining waste reservoir is shown in Figure 3. These are acquisition of observation data in a digital format, primary processing and automated design of 3D models of surfaces of controlled objects; digital high-accuracy positioning and determination of digital plan and elevation coordinates; digital velocity (sub-engineering-geological sections, creation of 3D calculation models, hydro-geomechanical 3D modeling with the output of numerical and graphical results in a digital form, etc.).

Diverse (in terms of methods) digital data are concentrated in a single data bank for further analysis and processing, and comparison with the available scientific-technical and expert decisions (regulatory and methodological documents) in the knowledge base.

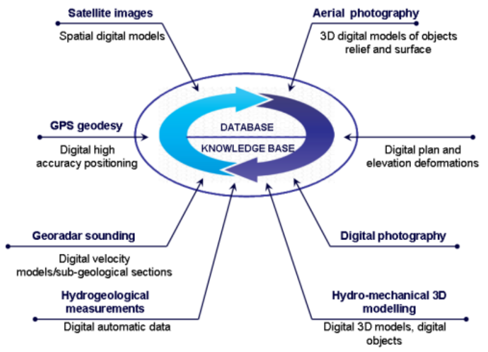

Figure 3: Application of digital technologies in monitoring of hydro-geomechanical conditions of a tailings dump.

3 RESULTS

Methodological approaches to multilevel application of interdisciplinary observation methods and digital technologies in monitoring the liquid mining waste reservoirs state have been tested at the principal large mining enterprises of the Barents Euro-Arctic region (Western part of the Russian Arctic sector) (Kalashnik, 2020; Melnikov, et al., 2018).

The entire set of the above methods and multilevel interdisciplinary observations have been used to monitor liquid mining waste reservoirs at Kovdorsky GOK (since 2012), Kola MMC (Pechenganickel) JSC (since 2014), and NWPC (since 2015). There were constructed specific observation sites equipped with geodetic benchmarks and surface markers, hydraulic control and measuring equipment, permanent reflectors and reference points for aerial photography and satellite image geo-referencing. The monitoring observations are carried out monthly, except for December-January (the Polar Night period in the Euro-Arctic conditions), in a spatial-temporal coordination, and, in some cases, were synchronized by combining visual observations, photo-fixation, GPR sounding, and hydro-geological measurements (Maksimov and Dyakov, 2021). During the summer months (the Polar Day period in the Euro-Arctic conditions), the above observations include additionally geodetic surface and GPS measurements by observation reference points; aerial photography and satellite optical and radar imagery data. The changes in the state of the liquid mining waste reservoirs, taking into account flooding and off-project loads, are forecasted based on the results of the scenario hydro-geomechanical 3D modeling (Kalashnik, 2019; Kalashnik, 2020).

On the basis of the obtained monitoring data, specialists established main regularities of the conditions of a particular storage facility, revealed the trends of condition changes due to operational filling, and designed adaptive 3D models (Figure 4).The filtration stability of the tailings dams was assessed; potentially dangerous filtration-deformation processes were identified and localized; and mechanisms of increased filtration and formation of filtration channels were determined (Kalashnik, 2019).

The water infiltration mechanism from the tailing pond into the Zhelezny open pit (Kovdorsky GOK) was determined: three zones of mechanical suffosion with increased filtration characteristics are formed in the enclosing embankment dam (Kalashnik, 2020; Melikhov, 2021).

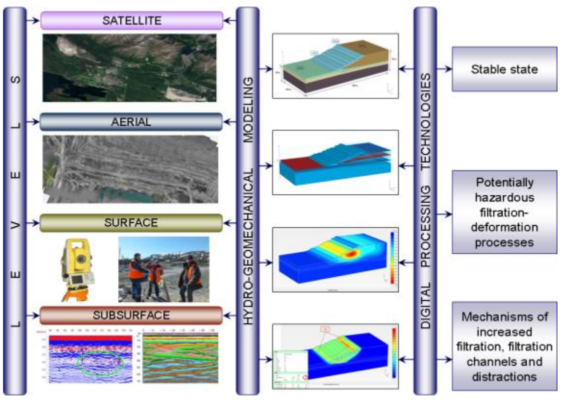

Figure 4: Application of interdisciplinary observations and digital technologies in multilevel monitoring of liquid mining waste reservoir to reveal the formation mechanism of potentially dangerous filtration-deformation processes.

Based on the monitoring results, protective and preventive measures were developed, which made it possible to prevent and avoid destruction of the reservoir. During the monitoring period, several hazardous areas were identified, which were promptly reinforced (backfilling with coarse plastic soil on the downstream slope, backfilling with finely dispersed soil and compaction of the embankment shelves).

In addition, a number of operational tasks were solved for the reservoir and hydraulic engineering structures of mines (2016-2019) owned by KB Apatit and OLCON (2015-2021). Monitoring studies were carried out at the hydraulic facilities of the tailing ponds located at the Vostochny mine (KB Apatit), and detailed information was obtained on the structure and conditions of the enclosing structures.

The specific monitoring activities at the reservoir of OLCON JSC included determination of the water inflow and outflow in the hydraulic facility's basin, drawing up a water balance and identification of its importance in the technological chain of the dressing plant.

4 RESULTS DISCUSSION

The multilevel monitoring of the liquid mining waste reservoirs located at the Barents Euro-Arctic region has showed high efficiency of the obtained results in the Arctic conditions. The application of interdisciplinary studies and digital technologies, both in observation and in data processing and interpretation, made it possible to improve the detail, information value, and reliability of the obtained multi-format data.

The application of interdisciplinary studies and digital technologies in multilevel monitoring has also allowed solving different-scale tasks: from the reservoir as a whole (tens of square kilometers), to its individual structures (kilometers and hundreds of meters) and their local components and sites (meters and fractions of meters). The data obtained at each observation level provided a framework and allowed proceeding in a hierarchy from the entire reservoir (satellite imagery), to the tailings dam (aerial imagery), its surface deformations (surface survey measurements), and to filtration-deformation processes (GPR, seismic, and hydrologic observations).

The results of level in-situ observations (satellite - optical and radar images; aerial - elevation plan, orthophotoplane; surface - geodetic plan and elevation displacements of reference points and marks; subsurface - radarograms (sub-engineering-geological sections), seismograms, depression surfaces) were very effectively supplemented by situational and scenario hydro-geomechanical 3D modeling of filtration-deformation processes. Modeling was also aimed at solving the tasks of assessing the stability of tailings dams for the current moment and for the medium term.

The use of digital technologies in the multilevel monitoring of the reservoir has allowed more reasonable and reliable state assessments and reveal of the formation mechanisms of potentially dangerous filtration-deformation processes.

Experience has shown increase of the information value and efficiency of the results obtained when using the interdisciplinary studies and digital technologies, both directly in observation methods and in the processing of multi-format data.

5 CONCLUSION

The research significance is to substantiate the application of interdisciplinary studies and digital technologies in monitoring of liquid mining waste reservoirs and to optimize their combination for solving specific monitoring tasks in the Euro-Arctic conditions. The monitoring uses interdisciplinary observation methods and digital technologies at different levels, both in carrying out observations and in the processing, interpretation and analysis of the obtained multi-format data. At the same time, the monitoring tasks are solved in the hierarchy from the reservoir, as object as a whole (tens square kilometers), to individual facilities (kilometers and hundreds meters) and their local components and sites (meters and fractions of meters).

The created basic principles allow achieving more detailed and reliable goals of operative diagnostics and assessment of the liquid mining waste reservoir state, timely detection and localization of areas with decreased reliability and functionality, continuous multiscale monitoring of potentially dangerous filtration-deformation processes and forecast of the reservoir functionality under different scenarios.

It is shown that the use of digital technologies both in the applied monitoring methods and in the unified processing of multi-format digital data increases the information value and efficiency of the results obtained. Digital technologies allowed more reliable assessment of the liquid mining waste reservoir state, and also contributed to the disclosure of the formation mechanism of potentially dangerous filtration-deformation processes in the tailings dams.

ACKNOWLEDGEMENTS

The work was carried out within the framework of the research topic FMEZ_2022_0009.

REFERENCES

Alabyan, A.M., Zelentsov, V.A., Krylenko, I.N., Potryasaev, S.A., Sokolov, B.V., Yusupov, R.M., 2016. Creation of intelligent information systems of operational forecasting of river floods. In *Vestnik of Russian Academy of Sciences, T. 86, no. 2, pp. 127 – 137*.

Antonov, V.A., 2021. Methodology for detection and forecasting of horizontal deformation of the earth's surface of adjacent rock blocks by GPS monitoring data. In *Mining Information and Analytical Bulletin, no. 5-2, pp.16-29.*

Bahkaeva, S.P., Guriev, D.V., 2016. Forecast of parameters of a tailings dam based on modelling of stress-strain state of the slope. In *Vestnik of Kuzbass State Technical University, no. 1 (113), pp. 12-17.*

Carmo, F.F.D., Kamino, L.H.Y., Junior, R.T. et al., 2017. Fundao tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. In *Perspectives in Ecology and Conservation, vol. 15, no. 3, pp. 145–151*.

Clarkson, L., Williams, D., 2020. Critical review of tailings dam monitoring best practice. In *International Journal of Mining, Reclamation and Environment, vol.34, iss.2, pp.119-148.*

Deryabin, S.A., Misineva, E.V.,2022. Design of a hybrid simulation model of the environmental state of the mining region based on the multi-agent approach. In *Mining Information and Analytical Bulletin, no. 4, pp. 169–181.* DOI: 10.25018/0236_1493_2022_4_0_169.

Hartwig, M.E., 2016. Detection of mine slope motions in Brazilas revealed by satellite radar interferograms. In *Bulletin of Engineering Geology and the Environment, vol. 75(2), iss. 2,pp. 605 – 621.*

Kalabin, G.V., Gorny, V.I., Kritsuk, S.G., 2016. Environmental assessment of the Kachkanarsky GOK territory based on satellite monitoring data. In *Journal of Mining Science, no. 2, pp. 179-187*.

Kalashnik, A.I., 2020. Integrated studies and monitoring of tailings of the Kola mining enterprises. In *Mining Journal, no. 9. pp.101-106*.

Kalashnik, A.I., Maksimov, D.A., Kalashnik, N.A., Dyakov, A.Yu., Zaporozhets, D.V., Melikhov, M.V., 2022. *Multilevel integrated studies and monitoring of tailings of mining enterprises in the northwestern part of the Russian sectors of the Arctic*, Apatity, FRC KSC RAS Publ., 250 p DOI: 10.37614/978.5.91137.465.5.

Kalashnik, N.A., 2019. 4D modeling of filtration-deformation processes in the tailings dam. In *Mining Information and Analytical Bulletin (scientific and technical journal), no. S37, pp. 393-400.*

Kovlekov, I.I., 2021. Safety of hydraulic facilities in the development of the northern deposits. In *Mining Information and Analytical Bulletin, no. 7, pp. 154-164.*

Kuchinskaya, G., Stavskaya, M., 2021. Application of surface laser scanning in modern conditions. In *Mining Information and Analytical Bulletin, no. 1, pp. 160-169.*

Kulikova, E.Yu., Konukhov, D.S., 2022. Monitoring of accidents' risk during underground space. In *Mining Information and Analytical Bulletin, no. 1, pp. 97-103*.

Maksimov, D.A., Dyakov, A.Yu., 2021. Monitoring of local violations of filtration processes in tailings dams of mining enterprises by a complex of geophysical and visual methods. In *Mining Information and Analytical Bulletin, no. 8, pp. 154–163*.

Maksimov, D.A., 2021. Dynamics of deformation and filtration processes at the site of the embankment hydraulic structure by visual monitoring data. In *Mining Information and Analytical Bulletin, no. 10, pp. 80-89.*

Melikhov, M.V., 2021. Geoinformation space monitoring of industrial safety of mining-hydraulic natural-technogenic complexes. In *Gidrotekhnicheskoe Stroitel'stvo, no. 10, pp. 2-9.*

Melnikov, N.N., Kalashnik, A.I., Zaporozhets, D.V., Dyakov, A.Yu., Maksimov, D.A., 2016. Experience of applying GPR subsurface studies in the western part of the Russian Arctic sector. In *Problems of the Arctic and Antarctic, no. 1 (107), pp. 39-49*.

Melnikov, N. N., Kalashnik, A. I., Kalashnik, N. A., 2018. Integrated multi-level geo fluid mechanics monitoring system for mine water works. In *Eurasian Mining, №2, pp.7-10*.

Mikhailov, V.O., Kiseleva, E.A., Smolyaninova, E.I., Dmitriev, P.N., Golubev, V.I., Timoshkina, E.P., Khairetdinov, S.A., 2016. Radar satellite interferometry: new technologies for satellite monitoring of mining areas, displacements of natural and man-made object. In *Science and Technological Developments, T. 95, no. 3, pp. 5-11*.

Morin, R., 2016. Satellite Remote Sensing for Effective Monitoring of Tailings Storage. In *Engineering and Mining Journal, December 2016.*

Musalev, D.N., Prokhorov, N.N., Klabuk, A.M., 2018. Experience of georadiolocation research in scientific and engineering support of mining operations at Starobinskoye potassium salt deposit. In *Mining Journal, no. 8, pp. 42-47*.

Napolskikh, S.A., Kryuchkov, A.V., Andrievsky, A.O., Cheskidov, V.V., 2017. Remote control of the stability of reclamation structures at the Stoilensky GOK. In *Mining Journal, no. 10, pp. 52-55.*

Ponomarenko, M.R., Kutepov, Yu.I., Volkov, M.A., Grinyuk, A.P., 2020. Space methods in the complex deformation monitoring of the earth surface of a mining enterprise. In *Mining Information and Analytical Bulletin, no. 12, pp. 103-113.*

Rybnikov, P.A., Buzina, D.A., 2021. Application of multispectral and hyperspectral data from aircraft and spacecraft to study mining areas. In *Mining Information and Analytical Bulletin, no. 11-1, pp. 55-70*.

Sashurin, A.D., Panzhin, A.A., 2020. Modern problems and tasks of geomechanics. In *Mining Information and Analytical Bulletin, no. 3-1, pp. 188-198.*

Tailings info. Tailings Related Accidents-Failures. Breaches and Mudflows, 2018. URL:https://www.tailings.info/ (access date: 26.03.2021)

Tikhonova, S.A., Struchkova, G.P., Kapitonova, T.A., 2021. Assessment of anthropogenic pollution of water bodies in Yakutia by spectral characteristics of satellite images. In *Mining Information and Analytical Bulletin, no. 12-1, pp. 213-222.*

World Mine Tailings Failures, 2018.URL: http://Worldminetailingsfailures.org (access date: 26.09.2021)

Zinovieva, O. M. M., Kuznetsov, D. S., Merkulova, A. M., Smirnova, N. A., 2021. Digitalization of industrial safety management systems in mining. In *Mining*

Information and Analytical Bulletin, no. 2-1, pp. 113-123.
Zongjie Lyu, Junrui Chai, Zengguang Xu, Yuan Qin, Jing Cao A, 2019. Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History. In *Advances in Civil Engineering.*
11 of the world's worst dam accidents, 2017. URL: https://www.vestifinance.ru/articles/81282 (access date: 12.02.2021).