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INTEGRATED MULTI-LEVEL GEOFLUID MECHANICS MONITORING SYSTEM FOR MINE WATERWORKS*

The article sets out a methodical framework of an integrated multi-level geofluid mechanics monitoring system for the mining and processing industry and illustrates the system implementation in the Kola Peninsula. The system is based on the multi-disciplinary observations, including ground-based and GPS (satellite) survey, geological engineering, hydrogeological and geotechnical measurements, aerial photography, geomechanical assessment, as well as subsurface, ground-based and spaceborn radar sensing. The structure of the system provides five monitoring levels, out of which the first four levels (subsurface, ground-based, airborn and spaceborn) are related with the daylight surface, while the fifth level (computer) means geofluid mechanics modeling and multi-version prediction in the analysis of various combinations of nature and technology impacts. The actual observations and subsatellite sites at waterworks of tailings ponds are illustrated in terms of processing plants of Kovdor GOK, Kola MMC, Oleniy Ruchey GOK and OLKON companies. Within the last 4 years, the integrated research into the state of these structures has been carried out jointly with the multi-level and different-scale scheduled measurements using check and control bench marks. From the obtained evidence, characteristics of the mechanical strength as well as permeability and deformation behavior of waterworks dams are revealed. The implemented research proves that the multi-level geofluid mechanics monitoring of waterworks within the systematic multi-disciplinary investigations enables early-stage detection of hazardous seepage, deformations and damages, as well as well-timed response and command decision-making to prevent emergencies and accidents. The experience gained in the integration of space, subsurface and ground-based radar sensing into surveying and hydrogeological observations makes it possible to state that the created system can efficiently be used in the geofluid mechanics monitoring of waterworks in the mining and processing industry.

Key words: *multi-level monitoring, multi-disciplinary integrated research, waterworks, mines*
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Introduction

In high-rate mineral mining and processing regions, there are many various-purpose waterworks which are potential hazard objects usually categorized as critical. Mineral mining considerably affects local natural systems, which results in violation of relative natural equilibrium of hydrological regime, activation of tectonic faults and crust movement. The latter can initiate hazardous events (subsidence, displacement, dislocation, landslide, rock bursts, earthquakes, gas outbursts, heavy water flooding, etc.). These events can become triggers of waterworks damage and failure, which brings considerable social and economic losses: toxic contamination of lands, rivers and lakes; destruction of closely spaced towns and industrial infrastructure, calamities, shutdown of mines and processing plants and, as a consequence, economic disbenefit in amount of hundreds millions of dollars [1–14].

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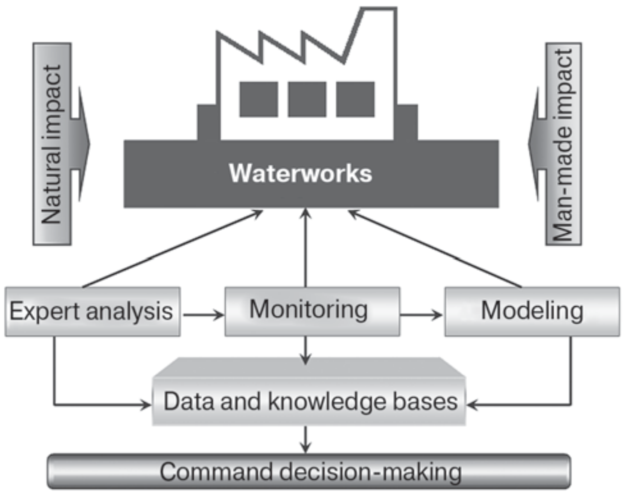

Fig. 1. Conceptual framework of waterworks safety

Concept of monitoring

The framework of industrial security of waterworks at mines and processing plants is the long-term and strategic decision-making on their mechanical stability and hydrodynamic operability under natural and man-made impacts [1, 5]. Natural impact on a waterworks structure means gravitational and tectonic forces, modern crust movements, processes in active geological faults, natural earthquakes, groundwater as well as surface and floodwater, etc. (**Fig. 1**). Man-made impact is produced by mining, blasting, large-scale displacement of rocks (overburden, dirt rocks, processing waste, etc.), liquid waste accumulation, industrial effluents, etc. The integrated impact changes mechanical stability and hydrodynamic operability of waterworks and the interrelated nature-and-technology environment.

A mandatory condition of waterworks safety is the integrated multi-level monitoring to disclose hazardous deformations at an early stage. Evidently, in this case, an important place belongs to the expert estimation of status and effectiveness of the waterworks structure, as well as computer-aided prediction and modeling of various scenarios of situation development [6]. With the monitoring data bases and theoretical knowledge, it becomes possible to make appropriate and timely decisions on accident or emergency precaution and prevention.

With this end in view, the Mining Institute of the Kola Science Center has created a multi-level monitoring systems for waterworks at mineral mines and processing plants in the framework of complexing inter-disciplinary in-situ observations and computer-assisted geofluid mechanics modeling. Different modifications of the monitoring systems have been trialed by large mining and processing companies in the Kola Peninsula: Kovdor GOK, Kola MMC, Apatit, Oleniy Ruchey GOK, OLKON GOK, as well as at waterworks supporting operation of hydroelectric power and heat plants, liquid industrial waste reservoirs of processing and metallurgy [6, 7].

Multi-level monitoring

In the system structure of integrated multi-level geofluid mechanics monitoring at waterworks, alongside with the traditional hydrological measurements, geodetic survey, seismics, laser methods, aerial photography, ground penetrating radar, satellite images and GPS technologies [8–11], it is proposed to use computer filtering and geofluid mechanics modeling [12] (**Fig. 2**). The monitoring is carried out on five levels, out of which four levels (subsurface, ground-based, airborn and spaceborn) are related with the daylight surface while the fifth level (computer) is 2D and 3D modeling, filtering and geofluid mechanics analysis.

Subsurface level. Permeability and deformation processes are controlled via automated measurements in piezometers and hydraulic observation wells. Seismic tomography allows adjusting moisture content and variation in the mechanic properties of dams down to a depth of 10 m. Ground penetrating radar offers highly informative and operational description of hydrodynamics of groundwater down to a of 40 m below surface, in real time and with GPS reference.

Ground-based level. Displacements and deformations of a waterworks structure and the adjoining geological environment are reliably and accurately determined using classic geodetic means (leveling and polygon measurements). One of the principal conditions is the transmission and confirmation of reference point coordinates (key factors of monitoring). Stability control of complex ground surface waterworks of mining and processing industry infrastructure in the Kola Peninsula involves laser and radar scanning.

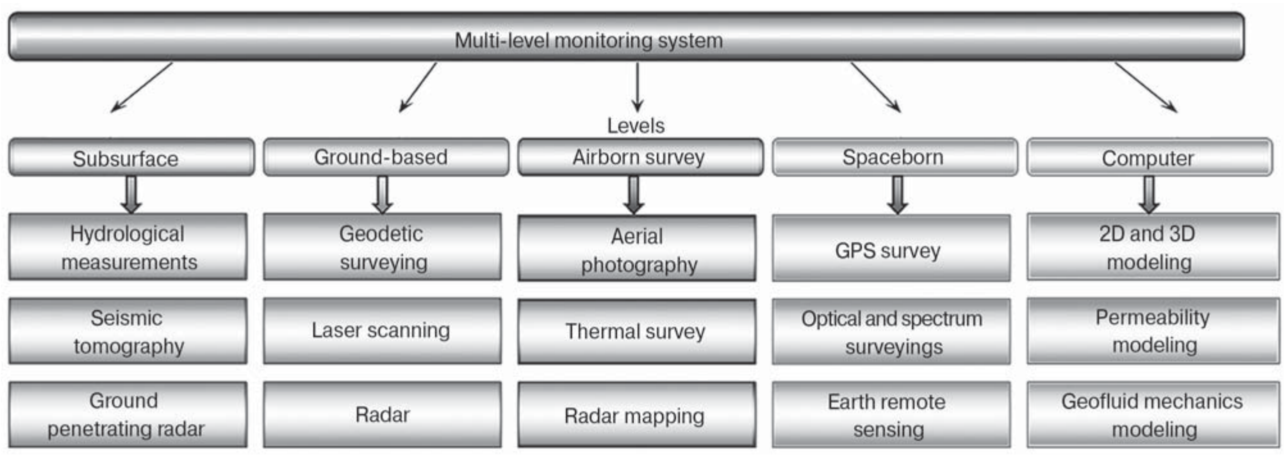

Fig. 2. Structure of multi-level geofluid mechanics monitoring at waterworks

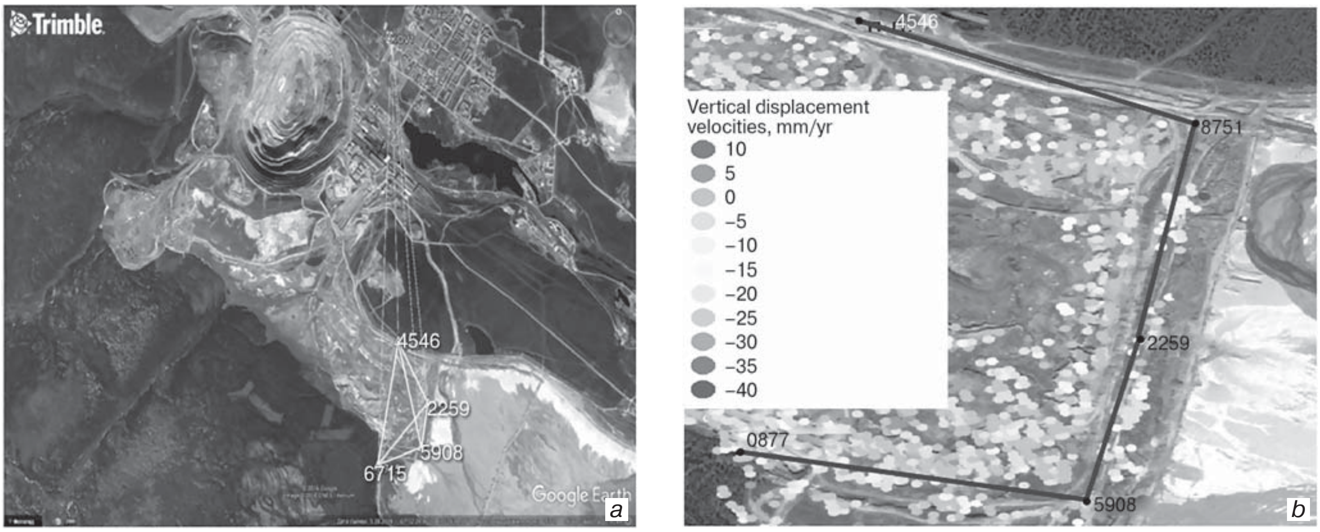

Fig. 3. GPS measurements:
a **— and velocity map of vertical displacements by the interferometric interpretation of Sentinel-1A images;** ***b*** **— in the area of tailings pond at Kovdor GOK**

Airborn level. Monitoring of spatial or extended linearly waterworks uses aerial photography and digital processing of optical, thermal and radar images taken by unmanned aerial vehicles (UAV). The chosen UAVs are both plane and helicopter types, and can perform automated air photography and image processing using photogrammetric program support. Based on the aerial photography and positioning (telemetry during flight, ground-surface reference points), 3D textured terrain model is constructed with the matrix of elevations and various-scale orthophotomap.

Spaceborn level. The planimetric coordinates of observation points were determined by GPS surveying technique named “statics” (sometimes “quick statics”) and by direct measurements. As an illustration, **Fig. 3*a*** shows the layout of control geodetic datums and GPS surveying at waterworks at the tailings pond of Kovdor GOK. The monitoring of the spatial and extended waterworks structures uses the data of digital processing of optical, spectra and radar images. The satellite cameras, depending on the optical axis incline, proved planimetric and isometric ground surface images of good geometry and high quality. The optical survey scales only depend on the photographic altitude and focal distance. Some images, if overlapped, are used to make aerophotographic mosaic or photomaps with location of reference points, which is sufficient for 3D modeling. Spectrum images assist in determination of properties of the surface under surveying and make it possible to solve ecological problems.

A feature of the radar imagery is its effectiveness in any weather and at all hours. In the radar images, the relief and surface roughness, moisture content and, sometimes, subsurface structures are well identified. For the purposes of monitoring spatial waterworks, the archived and operational radar imagery data after interferometric processing are used. The images are made both by Russian Resurs-M and Meteor-P and European satellites. In particular, the European Space Agency has given the present article authors access to radar data from Sentinel-1A\B which continuously survey in Interferometric Wide Swath mode, including the Kola Peninsula. **Fig. 3*b*** presents the map of the vertical displacement velocities based on the interferometric interpretation of Sentinel-1A images of the tailings pond at Kovdor GOK.

Computer level. For the purpose of determining permeability, deformations and variations in the conditions of waterworks, the integrated monitoring should involve computer-aided modeling using a dedicated software system (in particular, PLAXIS 3D). 2D and 3D models should be developed and adjusted based on the geotechnical, radar and hydrological instrumental measurements at least once a year [12]. Permeability modeling is aimed to predict and evaluate stability of waterworks structure. Geofluid mechanics modeling integrates geological-and-geometrical (geology and spatial char-

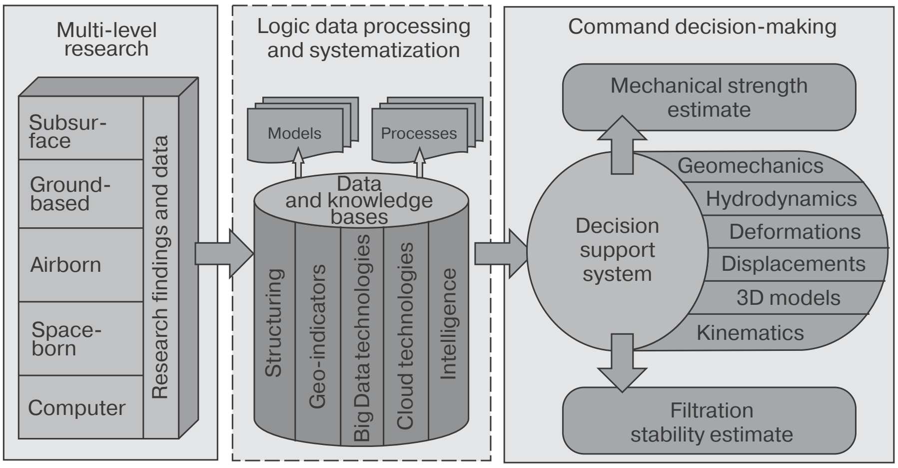

Fig. 4. Cognitive structure of integrated multi-level geofluid mechanics monitoring of waterworks in mining and processing

acteristics of soils), geomechanical (mechanical properties and effective loads), hydrostatic (water content of soil, dam top and bottom head differential, cone of depression) and hydrodynamic (formation of seepage zones, flow velocity and pressure) conditions. This allows combining geomechanical and hydraulic calculations to estimate integral reliability of waterworks.

Cognitive structure

The modern international and domestic monitoring systems use information technologies Big Data and Cloud Service with the elements of intelligence [13, 14]. The cognitive structure of the multi-level integrated geofluid mechanics monitoring proposed in this article for waterworks in the mining and processing industry includes three main modules: multi-level research; logical data processing and systematization; command decision-making (**Fig. 4**).

The multi-level research is the backbone of the monitoring system. The research and monitoring findings are continuously added to the data base. The Big Data and Cloud Service techniques are used for the data processing, systematization and on-line correlation with the available information. The decision support system, embracing laws of geomechanics and hydrodynamics as well as with regard to quantitative variables of permeability and deformation, assesses the risk of loss of mechanical strength and filtration stability. Thereupon, the preventive command decisions are made with a view to minimizing the risks.

In this manner, the proposed integrated multi-level geofluid mechanics monitoring of waterworks in the mining and processing industry has cognitive definition of objectives. The purpose is to create a set of methods, means and techniques to obtain and utilize new knowledge using elements of intelligence toward the next-level knowledge generation and, finally, intelligence monitoring system engineering. The related approaches are described by the Russian and foreign researchers [13, 14].

Conclusion

The Institute of Mining of the Kola Science Center, Russian Academy of Sciences, has created the multi-level geofluid mechanics monitoring system for waterworks based on the systematic inter-disciplinary integrated investigations. The observations carried out on different levels disclose hazardous seepage and deformations at early stage of their development in waterworks, which enables well-timed command decision-making on prevention of emergencies and accidents. The monitoring implementation at waterworks of the largest mines in the Kola Peninsula makes it possible to state that the created integrated multi-level system ensures efficient geofluid mechanics monitoring.

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