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THE STUDY OF THE STATE OF ROCK MASS DURING CONSTRUCTION OF UNDERGROUND RESEARCH LABORATORY AS A STAGE OF OBTAINING INITIAL DATA FOR THE SAFETY ASSESSMENTS OF DEEP GEOLOGICAL DISPOSAL

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Based on the analysis of foreign and local research experience in underground research laboratories and their analogues, as well as the requirements of safety justification tasks, the main directions of research work at the stage of URL construction are given. A brief review of the applied research methods is presented. The questions of combining research work performed from the earth's surface and from workings with the construction cycle of mining are considered.

Key words: *underground research laboratory, complex of in situ studies of the state of the rock mass, construction of URL.*

Suitability of a subsoil unit for deep geological RW repository construction is demonstrated via a multistage process involving research covering the studied region, site and area. In keeping with global practice, to perform detailed (extended) research and obtain the final confirmation manifesting the suitability of the selected area for deep RW repository construction, underground research laboratories are established and operated [1, 2]. Results of URL research should provide the bulk amount of data needed for relevant safety assessments and contribute to the demonstration of RW disposal reliability and safety on the whole. At the same time, representativeness and completeness of such field studies will contribute to a large extent to the credibility of the developed safety assessments.

In the near future, excavation of permanent openings pertaining to future underground research laboratory (URL) is planned in the Russian Federation [3, 4, 5].

Mining operations are seen as a most informative stage in terms of obtaining data on the structure and properties of the rock mass, processes occurring in it, as well as rock response to the mining operations. At this stage of URL construction, an opportunity emerges for a most detailed study of the rock mass structure at different hypsometric levels, for recording the distribution and internal structure of disturbance zones and sampling. Continuous impact of rock excavation activities along with relevant changes in natural and artificial physical fields of the massif can be also viewed as a source of

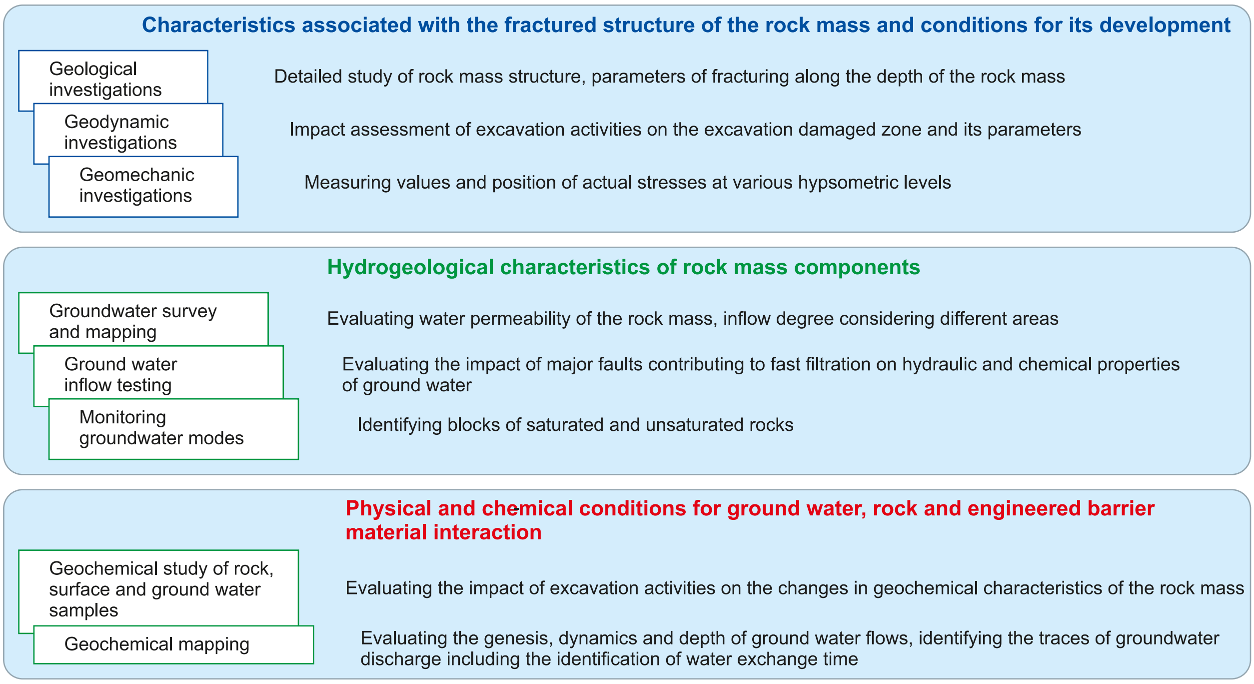

Fig. 1. Research tasks during URL excavation

information on its structure and potential groundwater flows. Thus, this period seems to be extremely important and should be considered thoroughly to obtain detailed information about the rock mass, as well as to gain the knowledge on the processes occurring in it.

Considering the above, present article is focused on a brief analysis of international and national experience of research in underground research laboratories and their analogues, as well as relevant requirements on the safety assessment tasks enabling to identify the key areas of research at the stage of URL construction [6].

In different countries, the issue of studying a rock mass at the stage of URL construction is addressed both via particular design solutions — excavations outlining the disposal area, research chambers at intermediate depth intervals, etc., and via the application of different research methods.

Since the URL developed in the Nizhnekanskiy rock mass is considered as part of the first repository section, particular attention should be paid to the choice of the measurement methods.

The results of research performed at this stage should involve the following:

- Elimination of existing uncertainties concerning the geological structure of the area purposed for facility construction;
- Refining the geological models developed earlier based on geological surveys;
- Obtaining data on physical processes and initial parameters of the rocks inside the rock mass. As rock mass is subject to impacts associated with the excavation activities, these parameters are impossible to be identified in the future;
- Evaluating the efficiency of engineering and technical solutions used in construction to ensure repository's safety;
- Identifying and estimating the changes in the geological environment during construction.

Moreover, regardless of the investigation stage associated with rock mass proposed for disposal facility construction, research results can be grouped according to the following initial data blocks [7]:

- parameters describing structural and tectonic structure of the rock mass: zones of discontinuous faults, zones with various degree of fracturing and genesis, monolithic sections;
- hydrogeological characteristics of rock mass components and groundwater flow parameters;
- characteristics describing the physical and chemical interaction of groundwater and rocks with engineered barrier material.

Types of activities are further considered based on the above areas (Fig. 1).

Underground research

Detailed study of rock mass structure, parameters of fracturing along the depth of the rock mass

Fracturing is considered as a most significant factor affecting the safety of RW disposal in crystalline rocks. Increased fracturing caused by mining operations and redistribution of stresses around the excavations increases the permeability of the geological environment with RW packages coming in contact with groundwater. Fracturing also affects the strength and stability of rocks; the nature and intensity of deformation occurrence; moisture capacity and water permeability; temperature mode inside the rock mass; its seismic characteristics, etc. It's considered a common practice to study fracture parameters to refine rock structure model based on the research of excavation rock outcrops, drill-hole cores, as well as the use of geophysical methods.

Study of rock outcrops is performed all along the excavations and within the area of lining detachment from the hole bottom [8]. The study involves mapping of loose sites (detailed geological description), characterization of rock composition, their structural and tectonic features, weathering degree, shape and size of jointing rocks. Major systems of cracks are visually inspected followed by description of their morphology at the surface, composition and structure of the crack filler. In the course of such evaluations, mass measurements of crack occurrence elements and their characteristic parameters are performed separately for each identified system: apparent length, aperture, filler composition, distance between the cracks.

Moreover, this stage involves sampling aimed at getting a detailed knowledge on petrological, mineralogical and structural characteristics of various rock mass components.

At the same time, this amount of research will enable to characterize the distribution of fractures along the depth of the rock mass. Thus, it seems necessary to supplement such measurement data by a set of borehole research methods also being used to identify the parameters of the disturbed zone outlining the excavations.

Impact assessment of excavation activities on the excavation damaged zone and its parameters

Since drilling and blasting method are planned to be applied for URL excavation causing an increase in the extent of excavation damaged zone (EDZ), attention in the course of research should be especially paid to the changes in fracturing along the depth of the massif. Fracture parameters of the rock mass both for the undisturbed state and the state evolved as the result of excavation activities are identified based on drilling and subsequent inspection of wells excavated for various purposes. A number of criteria such as specific granulometric composition and core yield are used to evaluate fracturing during drilling activities. This method is characterized by a number of disadvantages, namely, it's impossible to distinguish between naturally occurring fractures and those resulting additionally from the excavation activities. Yet another disadvantage is that it's rather difficult to monitor EDZ evolution over time (Fig. 2).

To distinguish between "natural" and "man-caused" fractures, particular URL research programs [10] provide for drilling of small diameter semi-steep wells ahead of the borehole excavation (along the design boundary) followed up by their backfilling with epoxy-based material. Drilling of this material after completing the excavation allows to identify and characterize the new cracks formed as the result of blasting.

EDZ evolution over time, including the EDZ formed as the result of impact associated with construction of neighboring excavations is evaluated via long-term observations providing for a complex of measurement flowcharts [12]. Identification of the undisturbed rock mass state is seen as an

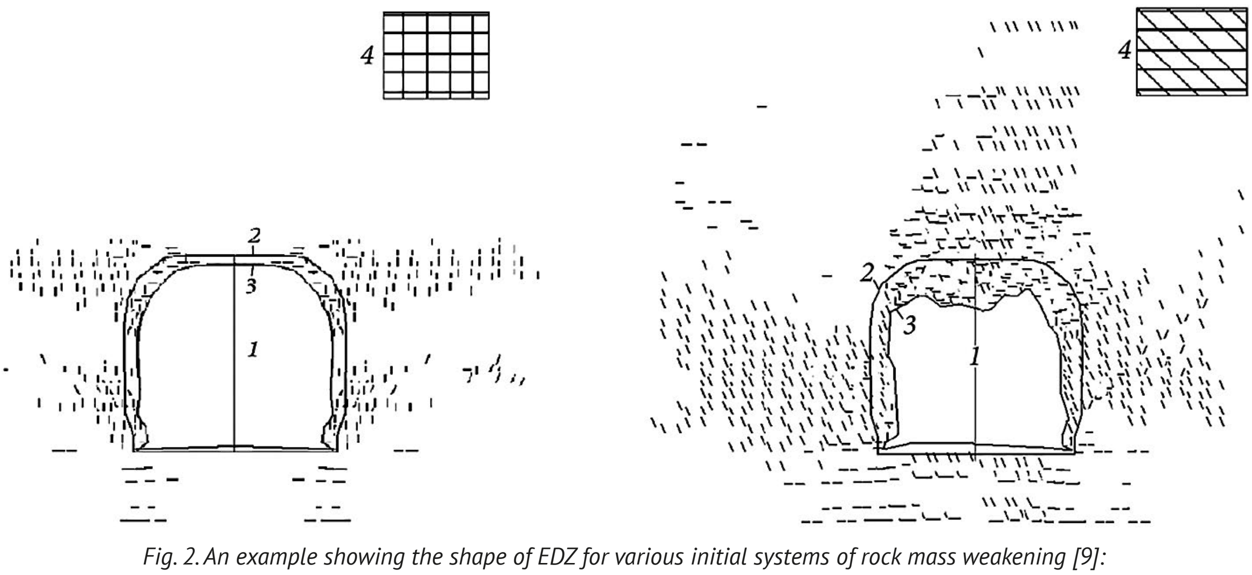

Fig. 2. An example showing the shape of EDZ for various initial systems of rock mass weakening [9]: 1 – excavation; 2 and 3 – contour of mine cross section: initial and deformed, respectively; 4 – orientation of the rock mass initial fracturing

important stage of such activities. Such complexes provide for a wide use of video and ultrasonic logging methods. Acoustic or optical video logging systems enable to capture a detailed 3D image of the borehole wall along the entire circumference and to address the issue associated with core evaluation, namely, to restore its orientation. Parameters describing crack aperture inside the rock mass are identified via acoustic methods. Such methods allow to evaluate the changes in the propagation velocities of longitudinal, transverse and surface waves, attenuation coefficients, as well as the frequency and phase spectra of elastic pulses.

Changing permeability of the rock mass resulting from EDZ development is estimated via selective flow tests performed in the wells drilled from the excavations. To enable a comprehensive assessment of the rock mass disturbance, it is advisable to drill such wells near relevant geophysical wells.

To identify the intensity of processes associated with EDZ development over time, process flow measurements of deformations along the production circuit are to be performed: at the stage of excavation drilling with a monitoring network extending along the rock mass depth; during operation.

Local areas with active crack formation are identified (as well as stress-strain state dynamics) via acoustic emission method [10, 11]. This method involves registration of elastic waves arising from the disturbances generated under the impact of various external and internal factors. Growth or closure of micro- and macrocracks, pore collapse— processes associated with changing structure of solids under the impact of various external and internal factors are considered as sources of acoustic emission in rocks. Under load impact, the disturbances are activated, thus, being capable of emitting acoustic emission signals long before macrocracking occurs.

Measuring the magnitude and orientation of actual stresses

Magnitude of the stresses and their orientation are seen as factors determining the occurrence of water conducting crack systems in the rock mass, thus, determining its permeability [15].

Drilling of vertical excavations to determine natural stress field and changes in its components with depth involves measurements carried out at several horizons in wells drilled along the strike, across the strike and at an angle of 45 ° to the strike of large tectonic faults.

Depending on the measurements location and the research stage, it is possible to use hydraulic fracturing, slot and front-end discharge methods, as well as their combinations with other methods [11, 13].

Thus, implementation of the above set of studies will provide information on the nature of fracture distribution starting from the excavation contour and extending deep into the rock mass, its stress state, elastic and strength properties, anisotropy and heterogeneity of rocks.

Hydrogeological research

Studying the parameters associated with ground water flow is yet another important area of research in terms of RW safe isolation in the underground environment.

Hydrogeological conditions in the excavated rocks at the stage of borehole drilling should be also studied during interval advancement of roadhead, rock mass exposure and research conducted to identify its water saturation parameters within the studied interval. The set of measurements performed includes visual characterization of rock mass water permeability, evaluation of filtration in different areas of discontinuities, identifying the dynamics of water flows along such discontinuities [15].

These methods are supplemented by geophysical ones being of a wide use when addressing hydrogeological problems with electrometry considered as the main one as it seems to be most sensitive to the changes in water saturation of rocks. Blocks of a rock mass with different water saturation levels can be identified based on the difference in their electrical resistivity.

In addition to the above methods, the use of fluid flow tomography [16] turned out to be a quite common internationally applied practice in determining the direction of groundwater flows over the mining progress and the expansion of underground excavations. This method is based on the measurement of groundwater flow potentially resulting from the interaction between flowing water and the artificial potential caused by electrodes installed at the ground surface.

Hydrogeochemical research

Groundwater sampling for chemical analysis and hydrogeochemical investigations are performed in parallel with hydrogeological measurements. This type of research is considered as a “direct” (and most reliable) method enabling to identify the links between the surface and groundwaters. Such identification is based on tracking and comparing the chemical composition of water in the recharge and discharge areas.

To determine the chemical composition of water under given underground conditions, samples are collected from exploratory wells drilled at various depths; drainage wells; water seepage points on the open surface of the rock.

Thus, analysis of water samples collected from recharge and discharge areas allows to estimate the time and the rate of its flow, to determine the links between the surface and ground water, to assess the impact that discontinuity zones produce on the hydraulic properties of the medium and groundwater chemical composition contributing to rapid seepage to significant depths.

Further study of groundwater hydrogeochemical mode covering the interval of the depths associated with URL underground excavations should be carried out based on stationary hydrodynamic monitoring stations. Thus, the excavation stage involves drilling of research and observation wells in the floor, walls and roof of the excavations.

Hydrodynamic stations are arranged in the areas characterized with largest discontinuities and within the nodes of overlapping tectonic zones.

Based on such investigations, water flow intervals in the rocks are determined, as well as their water saturation, filtration properties of various elements of rock mass, the nature of inter-interval relationships and the chemical composition of groundwater and other hydrogeological data.

Ground surface investigations

At the stage of excavation, a set of investigations conducted at the ground surface is aimed at obtaining the data required to explain the results of underground measurements, as well as identifying informative changes in physical fields occurred within the rock mass and caused by excavation activities.

Detailed description of structural-tectonic and geomechanical conditions inside the rock mass at URL site

To identify highly permeable disjunctive faults, high-precision horizontal and vertical measurements allowing to determine the location of structural-tectonic fault elements are performed, including [17, 18]:

- high-precision first class leveling from near faults;
- horizontal and vertical measurements enabling to identify the location of structural-tectonic disturbance elements;
- linear-angular measurements and first class leveling within geodesic triangles.

Based on the above measurement data, permeable zones are identified, quantitative assessments of the relationship between the disintegration of the rock mass caused by technogenic and natural factors, hydrological and hydrogeological processes are preformed, stress state of the rock mass is simulated and forecasted with due account of the relationship with the rock permeability.

Reverse vertical seismic profiling using various vibration sources originating from the underground excavations is yet another method enabling spatial detalization of structural-tectonics and geomechanical rock conditions around the excavations during their construction which is now considered as a quite common technique in URLs being developed abroad [19, 20]. During these studies, geophones are placed on and around the construction site.

Hydrogeological and hydrogeochemical research on the ground surface

Meteorological observations, control over groundwater level and soil moisture content on the surface — identifying the indicators considered as the basis of water-balance studies, should be continued at the construction site to evaluate the conditions associated with formation of groundwater flows. Control observations performed within a regular network of wells and enabling to detect the deformation of the underground water surfaces during construction is considered as a good source of information confirming the location of permeable disturbance zones.

Groundwater sampling within an available network of wells and surface waterflows conducted for laboratory chemical analysis purposes suggests identification of marker elements (identified at other geochemical monitoring stations) and is viewed as a necessary step in determining groundwater recharge and discharge areas.

Emanational (radon method) and helium surveys are considered as an important supplement to geological and geophysical activities enabling to evaluate discontinuous tectonics of the rock mass. These studies, considered as main methods enabling to detect and map permeable deep-seated faults, are performed to identify such areas, assess their activity, genesis, dynamics and depth of groundwater flow (including duration (time) of water exchange), as well as to identify relevant discharge zones [21]. The set of research conducted includes field quantitative evaluation of helium and radon content in groundwater, bottom sludge and soil gases followed by their geological and geochemical interpretation.

Arranging for and harmonizing measurement and construction activities

Overview of measurement methods provided above and considered as basic ones for the majority of URL R&D programs implemented at the construction stage has demonstrated that the set of activities (Fig. 3) should involve both direct and

Underground research — Direct methods	*Underground research* — Indirect methods	Research areas	*Ground surface research* — Direct methods	*Ground surface research* — Indirect methods
Fracture mapping, core analysis	Borehole geophysical methods	**Structure of the rock mass**	Interpretation of satellite images, preliminary pedestrian geological survey	Surface and borehole geophysical methods, helium and emanation surveys
Measuring the components of a stress field. Monitoring over excavation profile and rock mass deformation, special research methods	Well logging, monitoring over emission signals in the rock mass	**Geomechanical processes**	Geodesic methods (horizontal-vertical, line and angle measurements)	Tectonic and physical reconstruction
Testing for underground water inflow, measurement of groundwater inflow associated with different faults	Electrometry (electrode potential logging, vertical electro sounding method) of a charged body. GPR survey	**Hydrogeological characteristics of rock mass components**	Monitoring the elevations of groundwater surfaces inside the surface network of wells	Identification of thermal abnormalities
Rock and ground water sampling for chemical analysis	—	**Physical and chemical conditions inside the rock mass**	Sampling of surface water for chemical analysis purposes	—

Fig. 3. Applied research methods to investigate processes occurring inside rock mass during URL construction

indirect research methods and is believed to be quite time-consuming in its essence.

Thus, international experience in performing similar R&Ds [22] has demonstrated that depending on the complexity of geological conditions, duration of operations associated with the examination of rock outcrops, fracture mapping and rocks and groundwater sampling may amount to 0.5—2 hours. As it comes to the measurements associated with the extent of rock mass disturbance caused by mining operations (performed to assess the compliance of drilling and blasting parameters with the repository safety requirements and, if necessary, their adjustment), the estimated time accounts for 2—4 hours per well. Moreover, stress field component measurements require up to 4—6 hours per each.

At the same time, according to the design documentation, shaft sinking will be performed according to a combined flow chart involving a sequence of operations providing for excavated rock removal and construction of permanent lining directly in the bottom hole space following wall advancement. The amount and duration of excavation operations is presented in table 1.

In terms of their duration and conditions of execution, the values indicated demonstrate that only part of sinking cycle operations will allow to combine them with the above research. Total duration of these operations will be sufficient to carry out only a small portion of the given research activities. Thus, sinking and measuring procedures should be interrelated from temporary, process flow and organizational perspective based on the evaluation of the requirements specifying spatial and temporal conditions of the research.

A possible option allowing to arrange such research in order to reduce the loads on the bottom hole space is seen in splitting the research into the following groups of activities:

Table 1. Flow chart of process operations on shaft excavation

Operation	Amount per cycle		Scheduled time	
	unit	amount	hour	min
RIH/POH	–	–	4	20
Blast-hole drilling	m	288	5	20
BB unloading	–	–	0	20
Hole loading	pcs	72	1	10
Equipment lifting	–	–	0	20
Blasting and airing	–	–	0	40
Equipment lowering, bringing the bottom face to a safe state	–	–	0	50
Excavated rock removal (phase 1)	m^3	205.5	12	15
Form setting	pcs	1	1	0
Dass concreating	m^3	23.8	4	0
Remaining excavated rock removal (phase 2)	m^3	68.5	4	5
Extension of ventilation pipes, pipelines for concrete supply and compressed air supply	m	4×4	4	0

- routine inspection at the face repeated with each shaft sinking cycle;
- measurements allowing work to be carried out with a slight backlog from face advancement;
- in-depth examination performed at individual elevations of the shafts or when advancing the face through rock mass sections subject to characterization;
- long-term measurements (monitoring) involving equipment installation.

Final decision on the methods applied, instrumental base for relevant measurements should be done based on their comparative evaluation according to the following indicators: stability of the measured parameter, labor intensity, time required for measurements, availability of relevant technologies. Thus, a program ensuring scientific support of mining operations should be developed with a requirement suggesting that the overall duration of construction activities shall not be increased.

Conclusions

1 The study of rock mass state during mining operations is considered as an important stage of research enabling quantitative assessments of HLW disposal safety. These activities are conducted with successive exposure of the rock mass occurring at various hypsometric levels, thus, an opportunity emerges to record the internal structure of the rock mass and fault zones, to take samples, to assess the impact of mining operations on EDZ parameters.

2 A set of research proposed in this paper is aimed at obtaining most necessary set of rock mass parameters the identification of which at further URL construction and operation stages seems to be impossible.

3 Detailed information on the spatial distribution of the disturbances during excavation activities allows justified siting of monitoring stations and purpose designed research to be done inside the rock mass at further stages of underground facility construction and operation.

4 A wide variety of measurement methods, as well as the combination of research and construction processes imposes temporary restrictions on arranging the experiments, thus, necessitates in harmonizing these efforts. This requires the development of a program providing scientific support to mining operations with an appropriate adjustment of excavation cycle parameters. However, such adjustment should not compromise the overall duration of the construction operations.

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