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Spatial characterization of the physical process parameters in rock mass during construction of the underground facility for the RW disposal

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Substantiation of the suitability of the subsoil area for the construction of a radioactive waste repository in deep geological formations is a consequential multistage process, including the studies on the scale of “district”, “site”, “plot”. In near future in Russia it is planned to start work on sinking permanent mine openings of the underground research laboratory (URL). The purpose of this article is to provide a brief analysis of international and local research experience in underground research laboratories and their equivalents, as well as the deep geological repository (DGR) safety requirements to determine the scope of work on scientific and technical support for the URL construction. A brief review of the applied research methods is presented on the following aspects: Parameters characterizing structural and tectonic condition of the rock mass – rupture zones, fracture zones of various origins, monolith areas; geomechanical characteristics (stress-strain state, deformability and strength); hydrogeological characteristics of the mass elements and groundwater flow patterns; characteristics of the physical and chemical processes of interaction between groundwater and rocks and materials of engineering barriers. *KEYWORDS:* Underground research laboratory; in situ set of research; condition of the mass; construction of URL.

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Introduction

Substantiation of the suitability of the subsoil area for the construction of a radioactive waste repository in deep geological formations is a consequential multistage process, including the studies on the scale of “district”, “site”, “plot” (Figure 1). For the purpose of performing detailed (extended) researches and final confirmation of the suitability of geological sites for the placement of the deep geological repository (DGR), the practice of establishing underground research laboratories is applied [*Blechschmidt,* 2010], OECD/NEA No. 78122 Nuclear Energy Agency. Underground Research Laboratories (URL), 2013.

The results of researches performed by such labs are to provide major data necessary for assessment of safety of the facility, and to contribute to demonstration of the reliability of the radioactive waste (RW) repository in general. The representativeness and completeness of such field researches will

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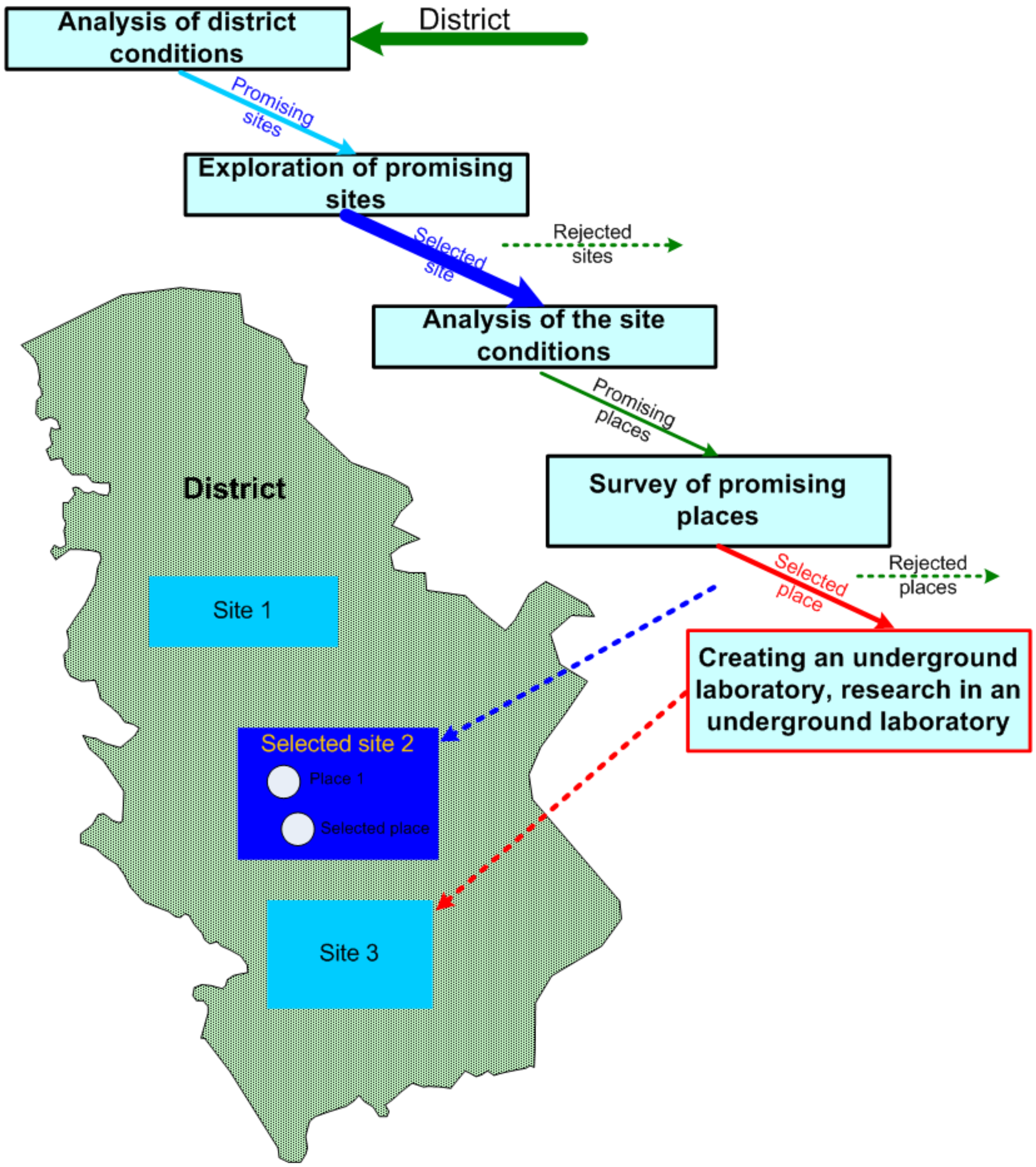


Figure 1. Stages of work to substantiate the suitability of the subsoil area for the radioactive waste repository facility [*Gupalo et al.*, 2005].

largely determine the credibility of the developed safety assessments.

At that, the key requirement of the contemporary safety assessments concept is the need to "build-up credibility" of the obtained assessments, based on the actual characteristics of the rock mass and guaranteeing isolation for the required periods of time (IAEA Safety Standards SSR-5 "Disposal of radioactive waste. Specific safety requirements").

I. e. for safety substantiation to be successful it should meet several criteria: favorable assessment solved by conscientious performance of a certain set of measuring and calculation procedures, and also the submission of safety case of the facility in the distant future, considering the influence of possible features, events and processes (FEPs) of a natural and man-made origin. Such assessment can only be performed based on a representative set of comprehensive field researches of the dynamic patterns of properties and depends on status of the engineering and geological elements of the facility after their long-term interaction, which requires consideration when planning the URL researches.

In near future in Russia it is planned to start work on sinking permanent mine openings of the underground research laboratory (URL) [*Kryukov,* 2018; *Rosatom,* 2018; Abramov A. A., Beygul V. P. The creation of an underground research laboratory on the site “Yeniseyski” of Nizhnekanski rock mass, available on http://www.atomic-energy.ru/articles/2017/08/22/78690].

The special feature of the planned stage of work – URL opening sinking – is the possibility to perform a detailed research of the structure of the rock mass at different hypsometric levels, to record the distribution and internal structure of the ruptured zones and to perform sampling. The resulting impact of driving operations on rocks with the accompanying changes in natural and artificial physical fields of the mass can also serve as a source of data on its structure and possible groundwater filtering patterns.

Due to this, the purpose of this article is to provide a brief analysis of international and domestic research experience in underground research laboratories and their equivalents, as well as the DGR safety requirements to determine the scope of work on scientific and technical support for the URL construction.

Selection of Research Areas

Safety assessment of isolation of the RW in DGR during the required time periods are based on estimates of migration of contamination resulting from the penetration of groundwater to the wastes and subsequent release of radionuclides through existing (natural) or additional (man-made) fractures. Consequently, the rock mass condition, will be characterized by physical processes and their benchmark indicators, which can change under the influence of natural (geodynamics, ground pressure, erosion, ...) and man-made loads (explosive impact during construction works, water disposal during operation, thermal impact of isolated waste) during the construction and operation of the facility.

Regardless of the stage of research of the rock mass planned for repository, the results of researches of these processes can be grouped into the following benchmark data segments [*Gupalo et al.,* 2005]:

- parameters characterizing structural and tectonic condition of the rock mass – rupture zones, fracture zones of various origins, monolith areas;
- geomechanical characteristics (stress-strain state, deformability and strength)
- hydrogeological characteristics of the mass elements and groundwater flow patterns;
- characteristics of the physical and chemical processes of interaction between groundwater and rocks and materials of engineering barriers.

In view of the above, further consideration of the types of work will be performed in relation to these areas.

Study of Natural Fracture of Rock Mass and Details of its Structure

Fracture is one of the most significant factors affecting the safety of RW repository in solid rock. The mass fracture indicators will also largely determine the strength and stability of rocks; nature and intensity of deformations; water capacity and permeability; temperature pattern of the mass; its seismic characteristics, etc.

The choice of research methods is determined by engineering and geological conditions, tasks to be solved, relief and geological features of the construction site [*Rac,* 1986; *Sergeev,* 1985; *Zelanski et al.,* 1981]. At the early stages of research, profiling techniques (on the earth’s surface) are used for spatial characteristics of large disturbances.

At later stages and while studying the man-made loads, a set of observation methods is used at the internal points of the rock mass – mapping, x-raying, logging – as more detailed one (Figure 2).

Due to this, the study of fracture parameters which clarify the model of the rock mass structure at this stage is based on the study of rock exposure along the entire length of mines, and is performed at the site of the temporary backlog of the mine support [*Magnor,* 2004; *Raven et al.,* 2007]. During the study, a mapping of loose areas (detailed geological description), description of the rocks composition, their structural and tectonic features, degree of weathering, shape and size of individual

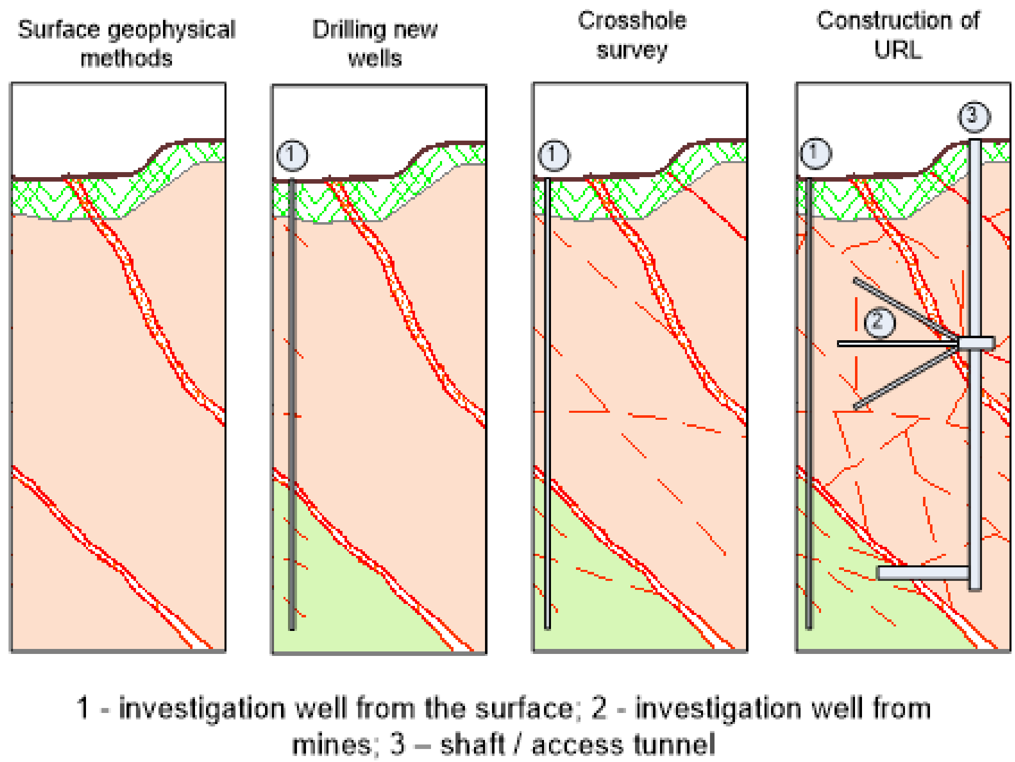


Figure 2. Stages of the rock mass structure research.

rocks is performed. The main systems of fractures with the description of their surface morphology, composition and structure of the filler are visually identified. This investigation also includes the mass measurement of the elements of the occurrence of fractures and their characteristic parameters such as the visible length, opening, filler composition, distances between the fractures etc.

Moreover, at this stage, the sampling is carried out to obtain detailed petrological, mineralogical and structural characteristics of various elements of the mass.

However, this scope of research does not allow to characterize the distribution of fractures at the depth of the mass. This determines the need to supplement the measurement data by borehole methods of research using a range of geophysical methods.

The practice of comprehensive geophysical studies shows that for many rocks there is a clear quantitative relationship between the speed of elastic waves, electrical resistance and fracture parameters. Table 1 and Table 2 present a statistical generalization of such characteristics of solid rock mass. [*Gupalo,* 2017; *Rac,* 1986; *Savich,* 1986; *Sergeev,* 1985].

At that, the elastic waves of 0.1 to 100 m in length are used to evaluate the properties of rocks varying from samples to mass. Accordingly, the method used for determining speeds from a few centimeters to several hundred and thousands of meters should also be changed. When constructing the graphs of speed change of elastic waves measured in different directions, a large scale curves are made that characterize not the general heterogeneity of the mass, but heterogeneity within the given directions (vector characteristics). The set of such vector graphs makes it possible to conclude on anisotropy [*Molokov,* 1987; *Nikitin,* 1981].

One of the ways to obtain such information about rock mass is to perform seismic micro profiling in mines and seismic logging in wells drilled perpendicular to their longitudinal axis [*Savich et al.,* 1969]. Measuring sites are equipped with an increment of 50 m along the length of the mines and the increment value decreases in case of opening of abnormal zones (tectonic zones or fractured rocks, areas of abundant water flow).

Table 1. Solid Rocks Features According to Geological Data

Degree of fracture	Description of rocks	Fracture index	Blocky structure, m	Total fracture opening, mm/m
Highly fractured	Highly weathered rocks, crumbled when struck with a hammer, ferrum oxides in fractures	> 25	$0.05 \times 0.05 \times 0.1$	10–20
Slightly fractured	Slightly fractured rocks, mildly weathered, solid	15–25	$0.1 \times 0.2 \times 0.2$	1–10
		10–15	$0.2 \times 0.5 \times 0.1$	1–2
		5–10	$0.5 \times 0.5 \times 0.3$	
Monolithic	Rocks with the presence of closed fractures, very solid, monolithic	< 5	$0.5 \times 0.5 \times 1.0$	< 1

The Research of Man-Made Fracturing and Assessment of the Impact of Driving Operations on the Size of the Disturbed Border Zone and its Parameters

Due to the fact that the opening sinking in URL is planned to be performed by drill and blast method, which causes the increased dimensions of the disturbed border zone, special attention in the course of research should be paid to changes in mass fracture depth [*Emsley et al.,* 1997; *Siren,* 2014, 2015].

Increased fracturing associated with mining operations and redistribution of stresses around the mine openings shall cause the increase of the permeability of the geological environment and the contact of RW containers with groundwater (Figure 3).

Indicators of fracturing of the mass, both in the natural condition, and as a result of driving operations are determined on the basis of drilling and subsequent inspection of wells of various purposes. Such criteria as the specific granulometric composition and core recovery are used to evaluate the fracture while drilling. The disadvantage of this method is the impossibility of separating the natural fracture and the additionally created as a result of driving operations. It also does not evaluate the development of the disturbed border zone through time.

To separate "natural" and "man-made" fracture, some URL research programs [*Raven et al.,* 2007] provide for drilling steeply inclined small diameter boreholes ahead of shaft sinking (along the design contour) and subsequently fill them with material based on epoxy resin. Drilling out of this material after the shaft sinking allows to identify and characterize fractures newly appeared as a result of blast work.

Assessment of the evolution of the disturbed border zone through time (including the result of the impact of work on the creation of adjacent mines) entails organization of long-term observations using a set of measurement processes [*Gupalo,* 2017].

Table 2. Change of the Sold Rocks Properties of Various Fracture Extent

Degree of fracture	V, km/s	ρ, Om/m	P, %	ρ, g/sm^3	σ, MPa
Highly fractured	0.4–3.5	50–100	4–6	2.5–2.6	20–80
Slightly fractured	2–4	100–300	1–4	2.6–2.7	80–110
Monolithic	5–6	300–1000	0.1–0.001	2.8–3.0	120–140

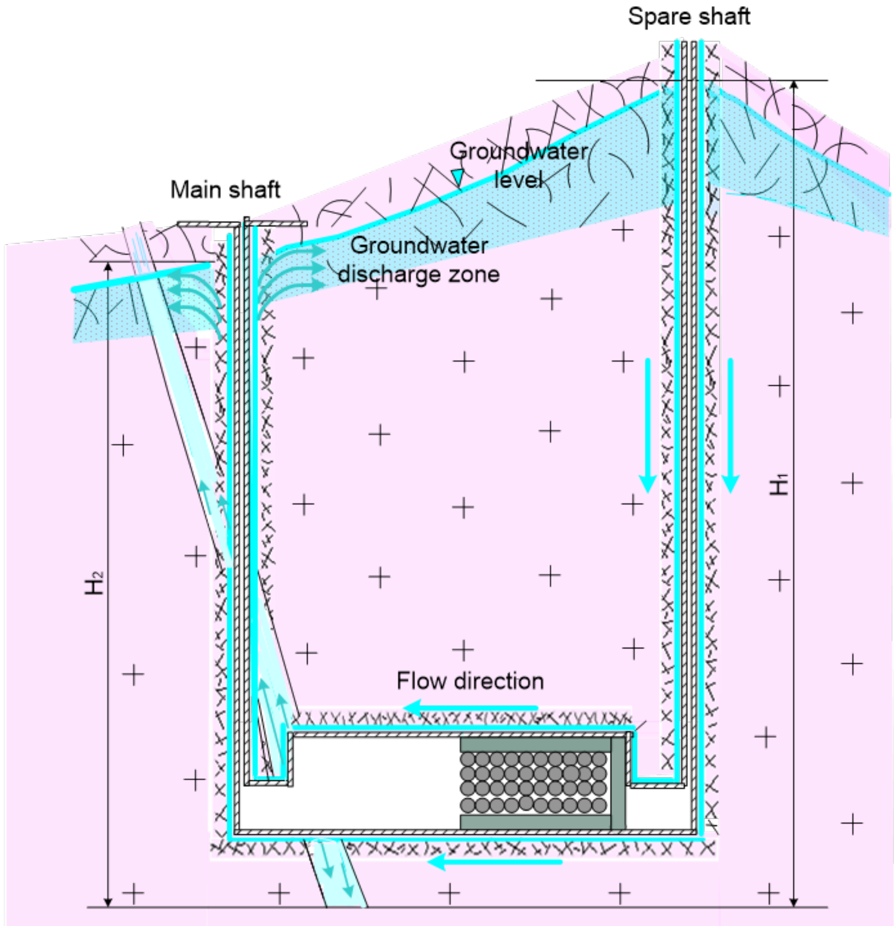


Figure 3. The role of the disturbed border zone openings in the formation of radionuclide distribution patterns during disposal.

In this case, identification of the initial condition of the mass is an important stage of such work.

Methods of video and ultrasonic logging have been widely used for such works. Systems of acoustic or optical video logging allow to record the expanded 3D image of the well wall along the entire circumference and to solve the problem linked to the analysis of core, dealing with restoration of its orientation. Evaluation of the mass fracture opening parameters is performed by means of acoustic methods – using changes in the propagation speeds of longitudinal, transverse and surface waves, attenuation coefficients, as well as frequency and phase spectra of elastic pulses.

At the same time, due to the importance of rock permeability indicators formed by the fracture system, an important task during safety assessments is to establish correlation relationships between the degree of disturbance of the mass and its filtration properties. Nowadays, there is only one way to establish such correlations, which is an experimental one. This determines the need to supplement the given scope of work by filtration methods. The change in the permeability of the rock mass, occurring as a result of the formation of a disturbed border zone, is estimated by the method of staged water injection in wells drilled from mines. For the purpose of the integrated assessment of mass disturbance, drilling of such wells shall be undertaken in close proximity to geophysical wells (Figure 4).

The process of establishing the intensity of the man-made fracturing development requires the organization of performance measurements of mine border deformations – at the stage of sinking, with the expansion of control points deep into the mass – during the operation period.

Identification of local areas with active fracturing (and determination of the stress strain behav-

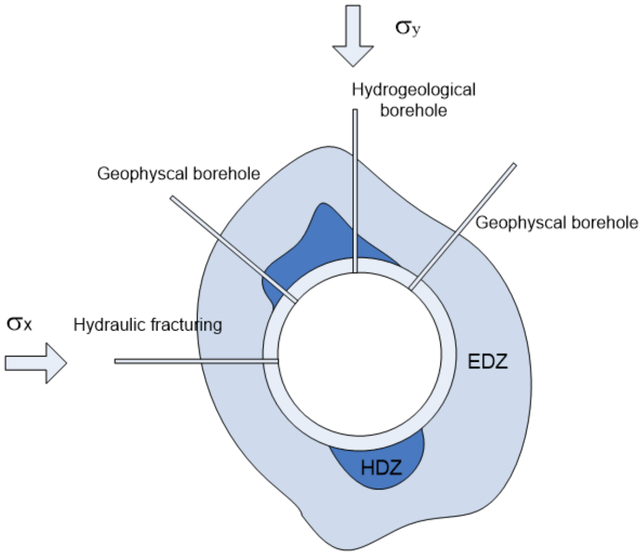


Figure 4. Combination of direct and indirect methods when studying the condition of the mass.

ior pattern) is performed on the basis of acoustic emission method [*Brojerdi et al.,* 2014; *Greshnikov and Drobot,* 1976]. The method is based on the registration of elastic waves resulting from the formation of defects under the influence of various external and internal factors. The acoustic emission in rocks occurs due to growth or closure of micro- and macro-fractures, pore collapse – processes associated with changes in the structure of solids under the influence of various external and internal factors. Defects are activated under the influence of loads, and the defects are able to emit acoustic and emission signals long before the occurrence of macro-destruction.

Researches conducted from the earth's surface represent an additional set of works at the opening sinking stage, aimed at spatial detailing of structural-tectonic and geomechanical conditions of rocks around the openings.

The method of spatial detailing of structural-tectonic and geomechanical conditions of rocks around openings during sinking is a reverse vertical seismic profiling. This method is widely used by the foreign URLs and presuppose the presence of various sources of vibration originating from underground openings [*Juhlin et al.,* 2002; *Yanitsky,* 1979]. For that purpose, geophones are placed at the construction site during the research process.

The emanation and helium survey serve a significant addition to the geological and geophysical work aimed at the evaluation of the fault tectonics of the mass. These researches, being one of the major methods of detection and mapping of permeable deep faults, are performed to identify such zones, assessment of their activity, assessment of the origin, dynamics and depth of groundwater circulation pattern (including determination of the duration (time) of water exchange) and establishment of their discharge zones [*Tsang et al.,* 2015]. The set of researches includes field quantitative determination of helium and radon content in underground waters, bottom silt and soil gases and their geological and geochemical interpretation.

Thus, the implementation of the mentioned set of researches shall provide information about the nature of fracturing from the opening border deep into the mass, its stress condition, elastic and strength properties, anisotropy and heterogeneity of rocks.

Measurement of Values and Directions of Stresses in Force, Deformation and Strength Properties

Stress values and their direction are the factors determining the occurrence of water conducting fractures in the rock mass and thus forming its permeability [*Markov,* 1978].

Currently, there are 3 different groups of methods of studying the stress state of rocks under conditions of their natural occurrence, which are fundamentally different in their physical basis [*Kurlenya et al.,* 1994; *AN USSR,* 1982; *Parfenov et al.,* 1984; *Siren and Hakala,* 2017; *Shkuratnik and Nikolenko,* 2012; *Tsang et al.,* 2005; *Zang,* 2010]:

- tectonophysical;
- geotechnical (complete or partial removal of stress, hydraulic fracturing);
- geophysical (ultrasonic, seismic).

Depending on the location of the measurements and the stage of the research, it is possible to apply the methods of hydraulic fracturing, crack and end unloading, as well as their combinations with other methods.

Thus, when sinking vertical openings, to determine the natural stress field and change of its components with a depth of measurement are performed at several levels of wells drilled along the course, across the course and at an angle of 45° to the large tectonic faults course.

At the same time, the direction of one of the wells should coincide with the orientation of future horizontal openings, and the other should be orthogonal to it. In this case, the stresses parallel and perpendicular to the axes of these openings will be determined, which is important for the calculations of their stability.

A significant addition to these types of work on the earth's surface shall be the implementation of high-precision compilation measurements of the location of the structural and tectonic disturbance elements, including [*Bulange,* 1978; *Tatarinov et al.,* 2014; *Zolotarev,* 1983]:

- high-precision first class leveling of close faults;
- compilation measurements of the location of the structural and tectonic disturbance elements;
- linear-angular measurements and first-class leveling in geodesic triangles.

Based on these measurements, the permeable zones are allocated, quantitative assessments of the relationship of disintegration of the rock mass due to man-made and natural factors with hydrological and hydrogeological processes are carried out. The reconstruction of the stress state of the rock mass as well as its forecast considering its relation to permeability are also performed.

Hydrogeological Researches

Another important area of work that determines the safety of waste isolation in the underground environment is the establishment of the groundwater flow patterns.

The study of the hydrogeological conditions of the host rocks at the opening sinking stage should also be performed in cycles continuously along the entire shaft wall. The set of measurements includes a visual characterization of the rock mass water permeability, assessment of the filtering capacity in different fractured zones, establishing the dynamics of their water inflows [*ONKALO,* 2003].

However, the main factor determining the filtration properties of solid rock mass is fracturing [*Chernyshev,* 1987; *Muller,* 1971].

In terms of their water permeability solid rock masses are generally heteroogeneous and anisotropic. Water flow patterns are explained by the nature of fracturing and the parameters of the largest fractures – their length, opening, wall morphology, degree and properties of the filling material. While assessing the hydrogeological features of a mass, fractures are divided into 4 classes by the type of a filler:

1. open;
2. filled with mylonite or tectonic breccia;
3. lodes covered by the material chemically deposited from the solution;
4. filled with loose weathering products.

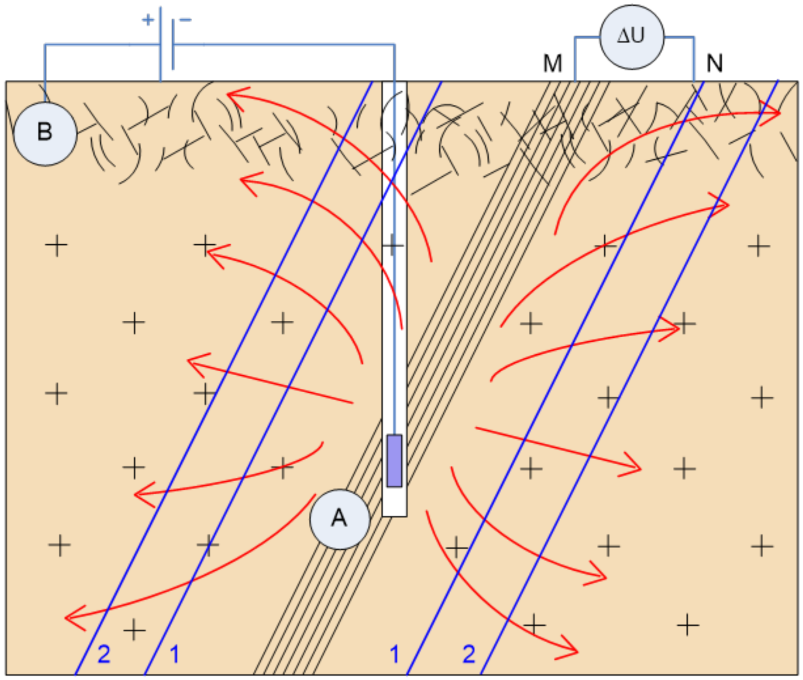
For the vast majority of rock masses water permeability is determined by macro-fractures. Open fractures of big length and degree of openness are characterized by the highest water permeability.

Large fractures filled with mylonite and tectonic breccia often serve as waterproof rock in the mass. However, their echelon fractures in the adjacent zone of the fault impact remain unfilled and are characterized by increased water permeability. The release of such flows to the surface is characterized by springs and other water seepages, which can be used to trace tectonical faults. It defines the information content and applicability of thermal logging.

Additionally, geophysical methods are widely used for solving hydrogeological problems, the major one is the electric logging due to it being most sensitive to changes in water saturation of rocks [*Chernyak,* 1987;; *Milsom,* 2003; *Telford et al.,* 2004]. Identification of mass segments with various water saturation is performed on the basis of the difference between their relative electric resistance.

For the purpose of determining the direction of groundwater flow during sinking and mine operations development, in addition to the abovementioned methods, the liquid flow imaging method has been used internationally [*ONKALO,* 2006].

This study is based on the measurement of the potential of groundwater flow resulting from the interaction between moving water and the artificial potential created by electrodes placed on the



AB - feed line; MN - receiving line; ΔU - measuring device;
1,2 - equipotential lines.

Figure 5. Functional diagram of the research using the charged body method.

earth's surface (Figure 5). Thus, the charged body method was widely used in Olkiluoto to study the location, continuity and nature of previously identified fractured zones in the openings area [*ONKALO,* 2003].

Hydrogeochemical Studies

Simultaneously with hydrogeological measurements, groundwater sampling is performed for chemical analysis and hydrogeochemical studies. Such studies are the "direct" (and most reliable) methods of establishing connection between surface and groundwater, and are based on the tracing and comparison of the chemical content of water in the area of accumulation and discharge.

The chemical content of water in underground conditions is determined by the sampling from: 1) research wells drilled at different depths; 2) drainage wells; 3) seepage points on the open rock surface.

To assess the conditions for the groundwater formation at the construction site, it is necessary to organize a monitoring survey in a regular network of wells on the earth's surface to detect deformation of the groundwater surface during construction. Sampling of groundwater in the well network and in surface watercourse for laboratory chemical analysis with the identification of marker elements (detected in other points of geochemical survey) is a necessary measure in determining the areas of groundwater accumulation and discharge.

Thus, the analysis of water samples from the areas of accumulation and discharge shall provide an opportunity to estimate the time and speed of its flow, to determine the relationship of surface and groundwater, to assess the impact on the hydraulic properties of the environment and the chemical content of groundwater in the fractured zones that contribute to rapid filtration to significant depths.

The subsequent research of the hydrogeochemical pattern of groundwater at the depth of the underground laboratory openings should be based on stationary hydrodynamic points. In order to do this, at the opening sinking stage, in the ground, walls and roof of the opening research and observation wells shall be drilled.

Hydrodynamic points shall be established at the areas of the largest disturbances and at the tectonic zones intersection.

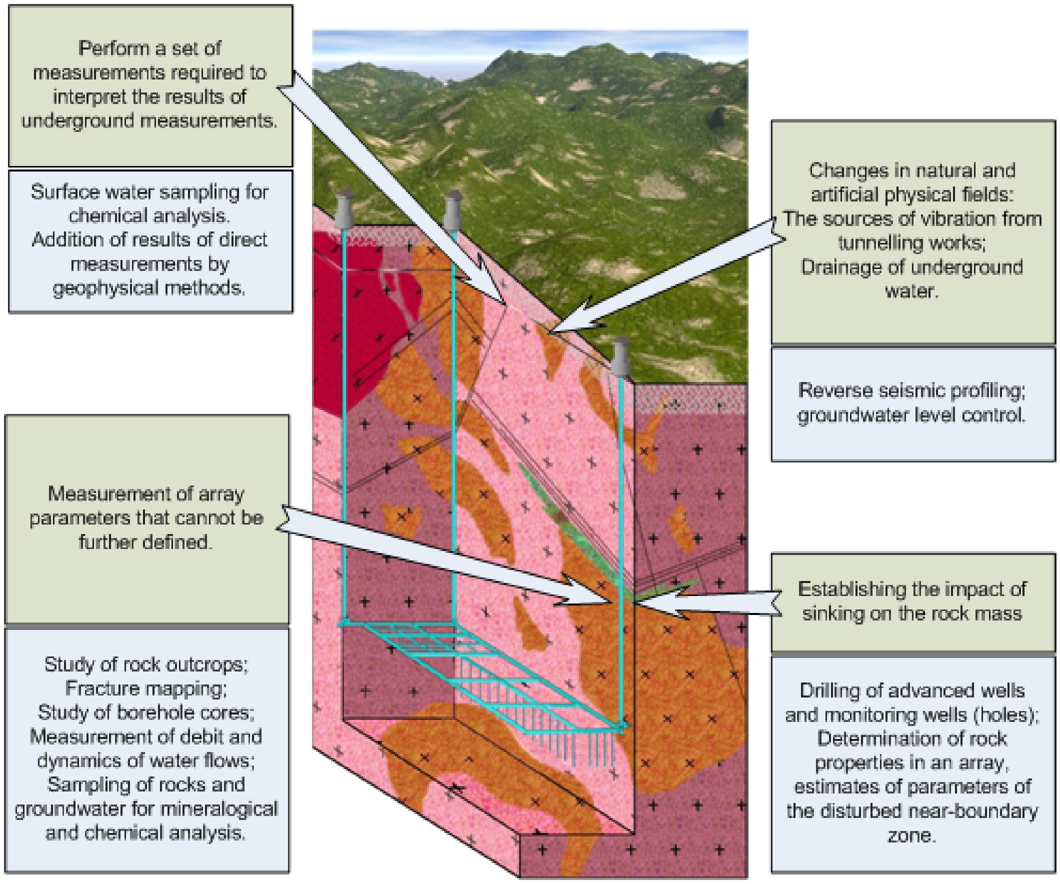


Figure 6. Combination of measuring and construction works.

Such studies result in the establishment of the rock water content intervals, their water abundance, filtration properties of various elements of the mass, as well as the nature of the inter interval relationship and the chemical content of groundwater and other hydrogeological data.

Synchronization of Research Works With the Sinking Cycle

The conducted survey reveals that the indicators defined for the DGR safety case can be obtained by direct and indirect methods. Direct methods make it possible to obtain accurate and reliable data in local areas of the mass. Indirect methods, performed from the earth's surface and from the openings, causing no disturbances to the continuity of the mass, offer the opportunity to characterize large areas. This determines the need for a set of such methods.

At the same time, the analysis of indicators of the sinking cycle revealed that only part of its operations in terms of duration and conditions of performance would allow their combination with research works. The total duration of these operations will be sufficient for performance of only a small part of the given scope of research activities. It determines the need for a temporary, technological and organizational link between the sinking stages and the measurement procedures.

One of the ways of such organization of research works (based on the assessment of requirements for spatial and time conditions of research), in order to reduce the load on the bottom hole area, will be their division into the following groups (Figure 6):

- regular inspection in the mine, repeated with each cycle of shafts sinking;

- measurements that allow for work with a small backlog from the mine face;
- a thorough examination performed on separate elevations of shafts, or when mine face passing through characterized sections of the mass;
- long-term measurements (monitoring), including the installation of equipment.

The final choice of methods, instrument base of measurement performance shall be made on the basis of their comparative assessment by indicators: stability of the measured parameter, work content, requied time spent on measurements, availability of technology. This determines the need to develop a program of scientific support of mining operations, one of the requirements to which will be non-increase of the total duration of construction process.

Conclusions

1. The given review of research works in foreign URLs, as well as contemporary requirements of safety case revealed that the study of the rock mass condition during mining operations with the definition of its benchmark indicators is an important stage of research.
2. Implementation of a representative field cycle of field studies is associated with the need to conduct at the opening sinking stage: in terms of detailing the geological and structural features and insulating properties of the rock mass, accommodating underground facilities:
    - detailed geological documentation of rock exposures; photo record of characteristic details of the geological structure;
    - mapping of fractures on the basis of mass measurements of elements of occurrence of fractures, with record of their morphology, density relationship, openness value, content of filler, study the internal structure of the fractured zones;
    - special studies of the rock mass fracture openness in undisturbed conditions;

   in terms of details of geomechanical conditions of a facility placement:

    - special studies of rock mass stress strain behavior;
    - high-precision compilation measurements of the location of the structural and tectonic disturbance elements;

   in terms of characteristics of hydrogeological conditions of adjacent strata:

    - measurements of water inflows in the fractured zones, identifying their water inflow dynamic patterns;
    - identification of watered and dry rock segments;

   in terms of the forecast of physical and chemical conditions of interaction of groundwater, rocks and engineering barriers materials:

    - groundwater sampling and preservation;
    - sampling of rocks (including filling material from disturbed areas) to study their material composition and physical and mechanical properties in the laboratory, formation of reference collections of rock samples, laboratory experiments with samples;

   in terms of assessing the impact of opening sinking work on the change in the properties of the mass:

    - characterization of disturbed border zones of openings in different parts of the mass;
    - assessment of the impact of mining operations on the rock mass, including the physical and mechanical properties and permeability of rocks;
    - special studies using pilot wells drilled from the mine openings, to detail the geological conditions of mine and change of the sinking modes.
3. Obtaining of such information is based on coordination of programs and methods of various types of direct and indirect ways of rock mass research, including:
    - comprehensive processing and joint analysis of the whole amount of the obtained data to forecast changes in the rocks condition;

- evaluation of changes in its insulating properties based on the establishment of correlation relationships.

4. Identifying the relationship between direct and indirect methods will provide an opportunity to assess the initial state of a mass, and subsequently use them to characterize changes in its properties.
5. A wide range of measurement methods, as well as the combination of research and construction processes impose time constraints on the experiments and determine the need to coordinate these works. This requires development of a program for scientific support of mining operations with appropriate adjustment of the parameters of sinking cycle, without breaching the total construction time.

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