Environmental Projection During Mining Diamond Deposits of Yakutiya with the Use of Grouting Curtains

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ABSTRACT

Mining of diamond deposits in Yakutiya at great depths both by open pits and by underground workings requires the need to pump and dispose of great quantities of highly mineralized ground water. This ground water has total hardness in excess of 170 mg.eqv./l with total dissolved solids up to 100 - 130 g/l and contains hydrogen sulphide. Disposal of this water into the hydrological network of the area which includes the Bolshaya Batuoba, Vilyui and Lena rivers results in the contamination of river waters and ruins their flora and fauna.

The reduction of mine water disposal to an allowable quantity is the radical method in controlling the detrimental impact of highly mineralized water on the environment. This can be achieved either by shutting off water inflows in underground excavations or by reverse pumping the mine water through wells which are drilled into permeable rock strata.

The paper descibes the planning and implementation strategy adopted during emplacement of a circular 2000 m long and 500 m deep grouting curtain around the biggest diamond pit in Yakutiya named "Mir" (peace from Russian). This programme demonstrates the feasibility of reducing the disposal of mine water into a hydrological network from the original 1750 m^3/h to 300 m^3/h. Details are given in respect to the parameters of the grouting curtain and design methodology.

INTRODUCTION AND CONCEPT ON ECOLOGICALLY SAFE GROUNDWATER PROTECTION SYSTEM FOR "MIR" DIAMOND PIT

Mining of the Yakutian diamond deposits is complicated by the problem of highly mineralized high-pressure ground water which form a huge regional basin in permafrost rock in the Western Yakutiya. In the area of the pit the water-bearing formation is encountered between 300 - 500 metres below the lower boundary of permafrost strata up to approximately 700 m. Therefore, during the first phase of open cast mining there were no indications of detrimental impact to the environment, i.e. ground water had not been exposed.

At the second phase, when excavation had to reach 450 m depth, mining proceeded under the protection of high - output dewatering system that consisted of dewatering wells paced around the pit perimeter and in-pit pumping facilities which regulated disposal of saline water into river network through retaining ponds.

The total discharge of dewatering wells amounted to 700 - 800 m^3/h, and with regard to occasional slippings to about 1100 m^3/h. The disposal of saline water into the river network was performed during spring - summer period and fluctuated in a range of 6.5 - 10.1 mln m^3 per annum. Within the period of 12 years of operating the dewatering system operation 63.6 mln m^3 of hydrogen sulphide-chloride-sodium brines with t.d.s. over 90 g/l was disposed into the local river network. This resulted in a drastic deterioration of the ecological environment in the basin of the Vilyui and Lena rivers.

The requirement to proceed with the third phase of the pit reconstruction which should provide for open pit mining up to 525 m depth put forward the problem of developing effective and ecologically safe protecting systems of mining activities against highly mineralized ground water.

The complexity of the problem consisted of the following:

- shortage of economically acceptable methods of water purification from dissolved salts;
- difficulties in determining the amount of safe disposal of highly mineralized water into the river network;
- shortage of experience in planning and constructing deep open pits in the hydrogeological environments characterized by high mineralization and containing hydrogen sulphide in high concentrations.

The scientific substantiation for design and emplacement of a circular grout curtain, called later counter-infiltration curtain C.I.C. around the ore body (see Figure 1) became the cardinal solution to the problem.

This structure has no analogy in the world practice and is a result of creative work of the experts from STG, Yakutalmaz Association and Yakutiproalmaz Institute. The complex of research, industrial trials and laboratory studies into the problem of C.I.C. was being accomplished in the following directions;

1. Detailed characterization of mining conditions, geology and hydrochemistry of the deposit.

2. Development of technology for creating deep grout curtains.

3. Development of highly effective grout compositions formulated from locally available materials and capable to form structure under low temperature and stable to corrosive impact of ground water.

4. Development of methodology for designing C.I.C. and quality assurance of grouting in the course of operations. The results of the aforementioned programmes were verified by experimental grouting at a trial site located on the northern flank of the pit.

Grout mixture was tested on a long-term basis for stability against corrosive attack. This testing was performed in the field with groundwater flows affecting the sample.

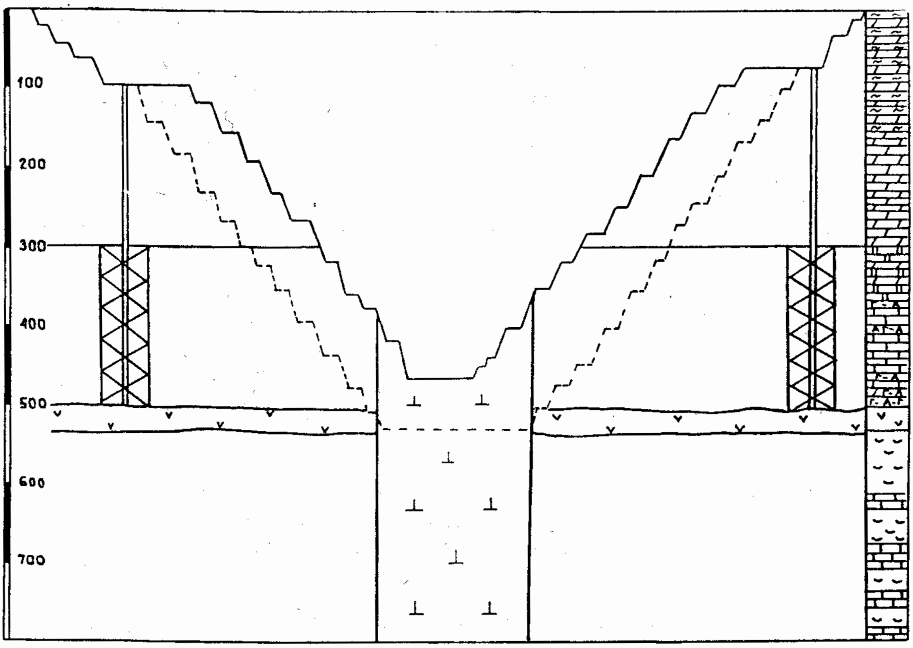

Fig.1 Schematic view of counter-filtration curtain at the Mir diamond open pit

Legend:

- current pit outline
- pit outline at the end of mining
- counter-filtration curtain
- kimberlite
- dolerite
- limestone
- dolomite
- marl
- siltstone
- gypsum-anhydrite
- rock salt

BRIEF CHARACTERISTIC OF GEOLOGY AND HYDROGEOLOGY OF THE "MIR" DIAMOND PIPE DEPOSIT

The surrounding rocks of the "Mir" diamond pipecan be attributed to lower Paleozoic period and are composed basically by terrigenous-carbonate, sulphate-carbonate and halogenic sedments. The rocks of the Metegero-Ichersky water-bearing sequence are characterized by strong variations of lithological content and are represented by dolomites and marls with inclusions of gypsum.

In terms of structural features the "Mir" diamond pipe deposit lies along the axial portion of the Parallel Fault zone, which has a width of 500 - 700 m according to geophysical data. In the course of exploratory and mining activities a great number of water-producing faults were detected.

The spacing of characteristic fracture systems of the deposit are shown in Figure 2. From Figure 2 there are three distinct groups of fractures:

1. A system of steeply dipping fractures with submeridianal striking (azimuth 17 degrees) running in the same direction as the Parrallel Fault. The fractures dip to the east at an angle 80 - 90 degrees.

2. A system of steeply dipping fractures with sublongitudinal striking (azimuth 281 degrees). This system reflects inhomogenity of strains during movements of separate tectonic blocks in the zone of the Parallel Fault. The fractures dip to the south at an angle 80 - 84 degrees.

3. A system of diagonal fractures with north-west (azimuth 310 degrees) and north-east (azimuth 40 - 50 degrees) striking, dip angles 80 - 90 degrees.

The total quantity of fractures encountered in the carbonate rocks of the Mategero-Ichersky formation amounts to 6 - 10 fractures per 1 m at a total thickness 0.2 - 0.3 m per 1 m. The apertures of separate fractures reach 0.2 m and more than 1.0 m.

In terms of the hydrogeological environment, the main source of water is a regional water-bearing sequence with a hydrostatic pressures of 17.5 - 24.9 MPa over its roof which is encountered in permafrost strata between 300 - 500 m. This water-bearing sequence can be described as a complex hydraulic system which interbedded by rocks with different hydraulic properties both vertically and horizontally.

Basing on the data of geological analysis and hydrogeological investigations, the "Mir" pit site can be conditionally subdivided into 3 zones: central, eastern and western. The biggest portion of water comes from the central zone where hydraulic conductivities vary from 0.83 to 2.2 m/day and permeabilities from 1.61 to 4.27 darcy.

Permeability of rocks at the western and eastern zones are lower and vary from 0.01 to 1.11 darcy.

The values of rock hydraulic properties geological data which were utilized for designing the C.I.C. around the "Mir" diamond pit are listed in Table 1.

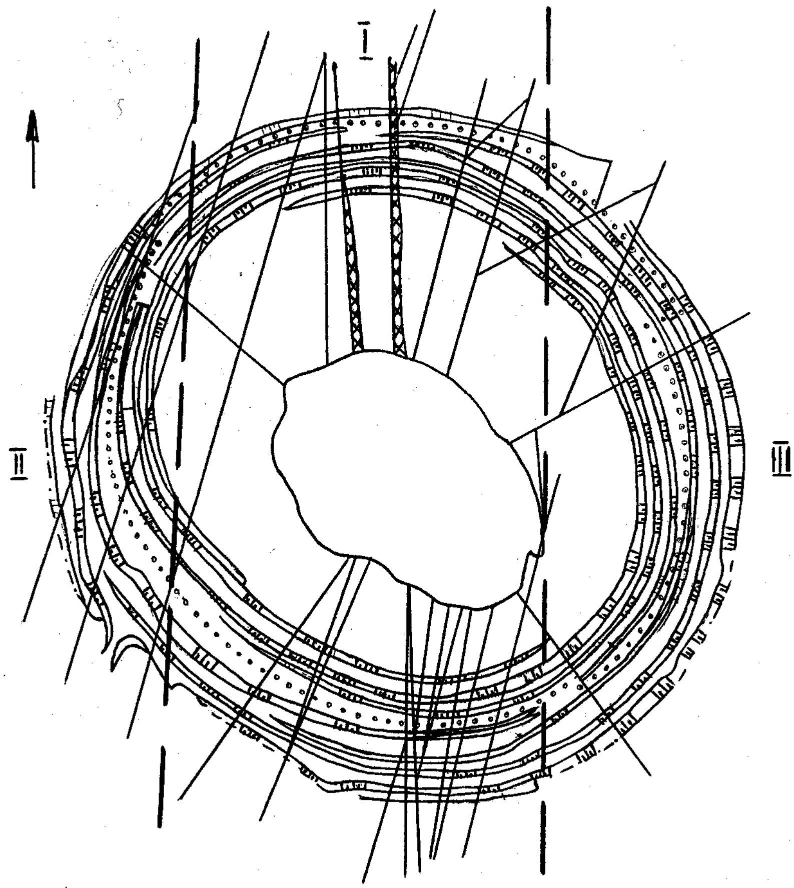

Fig.2 Structural features encountered in the Mir diamond open pit and location plan of counter-filtration curtain around the pit

Legend:

- grout injection borehole
- fault zone
- rock breakage zone
- I central structural zone
- II western structural zone
- III eastern structural zone

Table 1

Parameters	Units	Central Zone	Western and Eastern Zone
Permeability	m^2	4.27 x 10 - 12	1.11 x 10 - 12
Porosity	%	0.8 ÷ 1.1	0.5 ÷ 0.7
Maximum fracture aperature	mm	0.20	0.20
Minimum fracture aperature	m	0.15 x 10 - 3	0.15 x 10 - 3
Coefficient of fracture anistropy		0.55 - 0.60	0.55 - 0.60

Downhole geophysics indicated that water inflows originate from various intervals, the number of which varies in different holes and can range from 5 to 13 flow zones per borehole.

Ground water encountered in the Metegero-Ichersky sequence is a chloride-sodium brine containing chloride (47 - 51 g/l), sodium (28 - 31 g/l), sulphate (5 - 6 g/l), and also iron aluminium, silicic acid and other ions. Due to the high content of hydrogen sulphide the brines have an aggressive impact on concrete.

The process of grout formulation for the environment of the Yakutian diamond deposits included the following stages:

- identification of a basic material source for grout formulation,
- selection and testing of a binding agent as a basic structure-forming compound capable to hydrate under low temperature and stable to sulphate-hydrogensulphide aggression.
- selection of chemical reagents for regulating the process of structure formation and protecting the binding agent against corrosion.

Clayish tailings received from one of the ore processing plants were selected as a basic constituent of the grout mixture. The tailings consist of 60% of clay particles, 37% of dust particles and 3% of sand. in the chemical content there prevail silicate oxide (50%), aluminium (22%0, iron (3.5%), and also calcium, kalium, magnesium and others.

In terms of granulometric and chemical content the tailings are suitable for grout preparation. Alumina and sulphate-resistant cement were utilized as principle structure-forming agents. Auxiliary structure-forming constituents included sodium silicate and hypan.

To preclude grout freezing, sodium chloride was added into the mixture at a ratio 80 kg per 1 m^3. The following optimal grout formulation were selected for the project:

1. Clayish tailings with a density - 1 m^3
   of 1230 - 1330 kg m^3

   Sodium chloride - 80 kg/m^3

   Alumina cement grade 500 - 180 - 200 kg/m^3

   5% water solution of hypan - 20 kg/m^3

2. Clayish tailings with a density
1230 1330 kg/m^3 - 1m^3

Sodium chloride - 80 kg/m^3

Sulphate - resistant
portland cement grade 400 - 180 - 200 kg/m^3

Sodium silicate - 20 kg/m^3

Rheological and structural - mechanical of grout compositions are given in Table 2.

Table 2

Type of mixture	Plastic strength		Rheological characteristics	
	Pm after 1 min KPa	Pm after 10 days KPa	dynamic shear stress τ_0, Pa	structural viscosity η, Pa.s
1	> 0.50	> 675	100 - 150	0.06 - 0.11
2	> 0.30	> 516	80 - 130	0.05 - 0.08

With an objective to determine the aggressive impact of ground water on the grout mixture, studies were carried out into evaluating the corrosion resistance of the grout. The testing procedure consisted of placing samples of grout into containers with circulating ground water. These samples were recovered at specified periods of time and analysis was made to define chemical and phase content measuring as well as the strength of the sample. The study established that sulphate aggression was taking place, it was spreading frontally and in accordance with the diffussion law.

$$L = \sqrt{Kt}$$

where
L - aggression penetration depth,
K - time,
t - constant of corrosion process rate.

For the samples with alumina cement K = 0.25 mm/year and with sulphate-resistant content K = 0.85 mm/year.

The samples containing sulphate-resistant cement featured more extensive development of the corrosion process compared to the samples with alumina cement. However, even using the latter case, it was calculated that corrosion would not penetrate inside the curtain more than several centimeters within the period of 30 years.

BASIC ENGINEERING SOLUTIONS AND PARAMETERS OF THE COUNTER-FILTRATION CURTAIN

The designed outline of C.F.C. to be emplaced around the ore body mined by the "Mir" open pit had to consider the stability of pit walls and the full hydrostatic pressure that will build up on the completion of grouting (see Figure 2). The total length of C.F.C. amounts to 3000 m. and it is being created from the pit benches excavated at depths of 100 - 140 m through holes drilled up to 430 - 460 m.

Design parameters of C.F.C. are as follows: the curtain width in each water-producing zone, were calculated based on the maximal fracture aperture δ max, hydrostatic pressure P_k, allowable plastic strength of grout [Pm] and safety factor according to the formulae presented below:

$$R = \frac{d\,\delta_{\max} \cdot P_k}{2\left[P_m\right]}$$

The calculation results for central western and eastern zones are summarized in Table 3. The designed outline of grout spread from each borehole was determined from the condition of achieving pressure which will exceed the pressure of hydraulic widening of rocks and with account for rheological properties of grout and rocks:

$$r_{11} = \frac{\Delta P \,.\, \delta_{11}}{4 K \tau_0} \left[1 + \sqrt{1 + \frac{2 \beta_* \Delta P}{m_T}}\right]$$

where

- ΔP - pressure losses during grout preparation in rock fractures, MPa
- δ_{11} - minimal fracture aperture, m
- τ_0 - dynamic shear stress, MPa
- K - coefficient of viscous strengths
- m_T - fracture voidage (porosity)
- β_* - coefficient of rock elasticity, Pa

According to the calculation results, most fine fractures with an aperture 0.15 min will be sealed at a pressure of 17 - 21 MPa with grout spread radius of 12 m.

The choice of the optimal borehole quantity was made utilizing graphoanalytical technique taking into account orientation of major fracture systems and the coefficient of fracture anisotropy. This is illustrated in Figure 3. According to the results derived from the approach the most frequently spaced pattern of holes are in the central zone (northern and southern sites). The distance between holes of the 1st phase is 12 m with the possible concentration at separate sites up to 6 m.

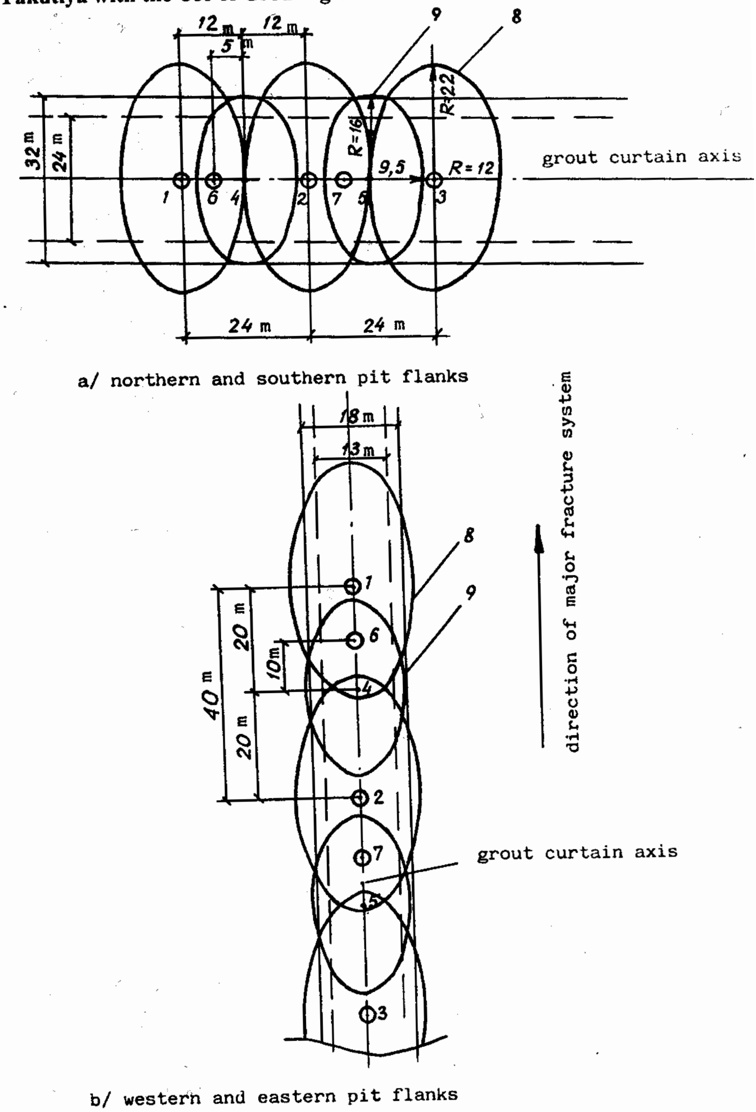

Fig.3 Scheme applied for selecting the optimal number of grout injection boreholes

1,2,3 - 1st stage boreholes, 4,5 - 2nd stage boreholes 6,7 - control boreholes of 3rd stage, 8,9 - grout spread outline, a/ - location of grout curtain across the direction of major fracture system, b/ - location of grout curtain along major fracture system

Towards the west and east, where the line of C.F.C. coincides with the direction of major fracture system, the distance between holes of the 1st phase amounts to 40 m, and of the 2nd phase it is 20 m, with the concentration at separate sites equal to 10 m. Borehole data are given in Table 3.

Table 3

Parameters	Units	Central Zone		Western and Eastern Zone
Calculated thickness of zone	m	24 - 32		13 - 18
Grout quantity per hole	m^3	1900		1330
Number of grout injection holes				
1 phase		60		37
2 phase		60		57
3 phase (reserve)			47	
monitoring			36	
Interval between grouting holes				
1 phase	m	24		40
2 phase	m	12		20
3 phase	m	6		10
Total amount of grout for implacing C.I.C.				
1 phase	m^3		189810	
2 phase	m^3		90090	
3 phase	m^3		27720	

The grout volume was defined on the basis of calculated grout spread outlines and fracture voidage (porosity) of rocks. The designed volume of grout quantity per hole of the 1st phase is 1900 m^3 at the central zone and 1300 m^3 at the western and eastern zones. The total quantity of grout injected in the formation of C.F.C. is 307620 m^3.

A programme of geophysical, flowmeter and hydrodynamic investigations was performed in the course of drilling. This contributed to introducing correctous in the designed volumes of grout injection into each detected permeable zone.

QUALITY ASSURANCE AND RELIABILITY CONTROL DURING EMPLACEMENT OF COUNTER-FILTRATION CURTAIN

The choice of the most reliable method of quality assurance for grouting operations is of a vital importance in ensuring minimal inflows into the pit during such a big-scale grouting project. The importance of this issue is due to the extreme complexity of mining and geological conditions, the inhomogenity of water-bearing sequence and presence of the permafrost at the roof and foot of the water-bearing sequence.

The following methods were utilized in the course of the programme implementation to verify the quality and reliability of operations;

1. Continous control over the properties of injected grout.

2. Control over actual and final parameters of grout injection process.

3. Analysis of grout injection regimes into each permeable horizon with regard for stress-strain condition of the grouted strata at a specific area with a continous record of the entire process and its computer interpretation.

4. Monitoring the changes in rock permeability in the course of grout injection. Comprehensive and reliable information about the grout injection regimes and rock permeability changes allows an assessment of the effectiveness of the grout treatment to be made This allows for the detection and elimination of the possble defects within the C.I.C.

The results received during placement of the 1st portion of the C.I.C. and measurements of the pit inflow reduction confirmed the high performance and effectiveness of the grout curtain performance.

CONCLUSIONS

1. The counter-filtration curtain with a length of 3000 m along the perimeter has up to a 32 m wide zone of grouted massif and propagates to the foot of water bearing sequence, i.e. 500 m deep. With the predicted pit inflow 1750 m^3/h the residual flow after injection will not exceed 250 - 300 m^3/h. This level of inflow planned to be managed at a specifically equipped treatment area for reserve pumping. This should provide for the mining of the total deposit without disposal of mineralized water into the river network, i.e. to maintain ecological balance of the area and not to effect considerably the environment.

2. The experience gained in engineering and emplacing the deep counter-filtration curtain at the "Mir" pit is extremely important for environmental management during open pit and underground mining of the Yakutian diamond deposits.