Interpretation of Sealing Pressure as a Method of Determining the Parameters of Sealing Cover around the "MIR" Diamond Pipe in Yakutia

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ABSTRACT

The emplacement of a sealing grout curtain around an open pit (diamond pipe "MIR" in Yakutia) has been developed by the Production Association SPETSTAMPONAZGEOLOGIA. The grout injection has proceeded by application of an operative control method.

Geophysical experiments during the process of sealing cover formation and numerical modeling of clay grout propagation in fractured rock taking into account the stress- strain state of rocks, has shown the following. The creation of a high efficiency sealing cover proceeds with elastic deformation of sealed fractures' walls. This process is accompanied with the process of hydraulic expansion of the rock, which forms a high residual pressure and provides its conservation for some time. Thus the reaction of fractured rock necessary for the creation of a quality sealing cover is achieved. High quality of sealing in the hydraulic expansion area is explained as follows. When the grout injection is finished, inverse deformations of the rock causes additional compression of grout in fractures, this ensures good adhesion with the rock.

The optimum regime for the grouting process is determined by an integrated method, which includes monitoring of grout injection parameters with the help of electronic instrumentation; mathematical treatment of this information and storage into a data base, which also contains technological, physical and geomechanical data. Interpretation of all this information for diagnosing the grout propagation regime, for determination of the dimensions of the grouting cover, and for estimating the quality of grouting cover takes place.

SOLUTIONS

Physical and numerical modelling

The sealing pressure is determined by solution of the hydrogeomechanical problem making the following assumptions.

1. Stress-strain state of sealed horizon should be taken into account. Stress-strain state of the rocks is determined with the help of finite element analysis using the computer program FEA. The program FEA was written in the St.Petersburg State University scientific group headed by A.M. Borovkov [1]. Numerical modelling is executed for axially symmetric and three-dimensional cases taking account of pit shape, existence of relaxation zones and anisotropy in physical and mechanical properties. Program FEA-MIR (application of FEA to open pit 'MIR" project) defines normal stresses in a local coordinate system associated with two mutually orthogonal

fracture systems. Rocks surrounding the open pit 'MIR" have big tectonic fractures and two fracture systems: submeridional (azimuth 17°) and sublatitudinal (azimuth 281°).

2. Clay grout propagation in fractured rock proceeds with elastic deformations of the fracture walls resisting normal stresses S_i. We consider: the bigger the deformations, the higher the quality of sealing is. This is explained as follows. When grout injection is finished, the inverse deformations of rock causes the additive compression of grout in fractures, its settlement and good adhesion with the rock. Thus, in the grout propagation area a non-linear regime of filtration may occur. Results of numerical modelling of fluid propagation along a single fracture [2], as well as experimental data [3], showed that the relationship between fracture width growth Δb_i, internal grout pressure P and compressive normal stresses S_i as follows:

$$b_i = C_i (P - S_i). \qquad (1)$$

C_i is a coefficient of rigidity which is determined from experimental data or can be estimated by the approximate expression:

$$C_i = 2 (1 - \nu) a_i / E_D, \qquad (2)$$

a_i - block dimension in the compressive stress S_i action direction,
n - Poisson's ratio,
E_D - dynamic Young's modulus.

A non-linear elastic regime fracture permeability tensor [K] determined by the submeridional and sublatitudinal fracture systems is as follows:

$$[K] = \frac{1}{12} \begin{vmatrix} \sum_i [b_i - C_i(P-S_i)]^3 \Gamma_i (1-Cos^2\alpha_{1i}) & 0 \\ 0 & \sum_i [b_i - C_i(P-S_i)]^3 \Gamma_i (1-Cos^2\alpha_{2i}) \end{vmatrix} \qquad (3)$$

b_i - initial fracture width,
G_i - fracture density (amount of fractures per 1 m),
$Cos\alpha_{1i}$, $Cos\alpha_{2i}$ - direction cosines in global coordinate system X_1 and X_2,
i=1,2 - two fracture systems.

We shall consider further that global axes X_1 and X_2 are directed to north and to east correspondingly.

3. Sealing grout is a non-Newtonian viscoplastic liquid characterized by the non-zero value of dynamic shear stress τ_0. Movement of grout begins only after the pressure gradient exceeds some limiting gradient G. G may be defined as a function of [K] and τ_0:

$$[G] = C\tau_0[K]^{-1/2}, \quad C = const \qquad (4)$$

or it may be defined from the sealing pressure treatment.

Viscoplastic liquid propagation in fractured media may be described by filtration law with limiting pressure gradient:

$$U^{\to}=[K]\,(gradP-[G]gradP/|gradP|)/\mu, \qquad g_i>0,$$
$$U^{\to}=0, \qquad g_i<=0. \qquad (5)$$
$$g_i=\sum_{j=1,2}(\Delta P/\Delta X_j-G_{ij}(\Delta P/\Delta X_j)/|gradP|),$$

μ - viscosity of grout.

Joining continuity equation for low-compressible liquid in fractured media

$$\beta\delta P/\delta t-divU^{\to}=0 \qquad (6)$$

(β - elasticity of rocks)

with filtration law (5), we obtain combined non-linear equations of filtration with limiting pressure gradient. Combined equations are enclosed with boundary conditions. At the borehole the variable grout injection rate Q is defined. At solution area boundaries pressure is equal to the initial pressure value.

The problem is solved numerically with the help of the finite differences method. Numerical modelling in a wide range of defining parameters was fulfilled. It has allowed the authors to apply simplified dependencies for calculation of the sealing pressure and residual pressure distribution along the line of grout propagation.

Residual pressure analysis

The Production Association SPETSTAMPONAZHGEOLOGIA has a great deal of practical experience in grouting of fractured and porous rocks. This experience has shown that residual grout pressure P_0 is closely associated with the sealing cover efficiency [4]. A high quality of sealing cover is achieved when P_0 is high and remains constant for some time. This "empirical law" can be explained as follows.

A non-linear elastic regime of viscoplastic liquid filtration we call "elastic sealing regime". During this regime grout is moving along a fracture as a plastic "stopper". Longitudinal movement of grout is defined by hydrodynamic theory and is accompanied with diametrical movement defined from an elasticity theory problem solution. Thus grout propagation along the fracture is accompanied with fracture width growth. When the grout injection is finished, elastic energy of the rock deformation accumulated during injection leads to "inverse" deformations of the rock. Grout is compressed by the fracture walls. It conserves a residual pressure P_0 which is commensurable or greater than compressive stress. Thus the value of P_0 may serve as a criterion for sealing cover efficiency. But it is the only necessary condition. Sufficient condition is the conservation of constant value of P_0 for some time. It means that in the sealing area there are no voids: sealing of voids might lessen the residual pressure.

Pressure losses

Injection pressure is registered at a control station located on the surface. Before the sealing pressure, can be interpreted, it should be calculated with account of pressure losses in the borehole and in piping. Pressure losses are found numerically with the use of the viscoplastic liquid flow resistance law. They depend on two similarity criteria: Reynolds number $Re = \rho U_{av} d/\mu$ characterizing viscosity influence and "plastic parameter" $II = \tau_0 d/\mu U_{av}$ characterizing plasticity influence. Here U_{av} is average velocity, d - tube diameter, ρ - grout density.

Technological solutions

Sealing pressure may be considered as a reaction of rocks to the injection of grout. This reaction depends on filtrational and geomechanical properties and the stress- strain state of rocks. Among all these factors only filtrational properties may be altered at the stage preceding the stage of high efficiency sealing. For example, the presence of wide tectonic fractures near the injection borehole means that at the first stage all of the sealing grout will propagate along this fracture. Consequently, background permeability (3) will not be sealed. Low sealing pressure and quick fall of residual pressure indicate the presence of such a fracture. Special efforts should be provided to avoid this result. Results of numerical modelling showed: it is necessary to increase the grout injection rate and reological parameters of the grout. Pressure losses in tubes also increase in that case, so an additional technological method is used: cyclic injection. Injection should proceed with prolonged stops sufficient for grout hardening in the magistral tectonic fracture. As the fracture is sealed, background permeability is included in the process of sealing. In that case grout injection should proceed very carefully to avoid grout break through the magistral fracture outside of the sealing area.

Another extreme situation is a low permeability area of sealing. A high grout injection rate and high reological properties of grout may result in damage to the rocks or even in development of horizontal fractures.

Regimes of sealing

From all the aforementioned it follows that sealing process should proceed under continuous control and analysis. This analysis should be based on diagnosis of the hydrogeomechanical processes in the sealing area. Following this hydrogeomechanical sealing models may be determined.

Horizontal fracturing: under conditions of the 'MIR" open pit development of horizontal disk-shaped fractures or horizontal grout propagation in layered formations could take place in impermeable rock without vertical fractures. It is a non-desirable process and it should be avoided where possible.

Injection of grout with high values of dynamic shear stress τ_0 and viscosity μ in low-permeability zones near boreholes or into the formerly sealed zone may be accompanied with vertical hydraulic fracturing along the direction of maximum confining stress.

In the "elastic sealing regime" elastic deformations of sealed fracture walls take place up to the point of shear failure in fractures or in surrounding microfractures. This process is accompanied with the process of hydraulic expansion of the rock. A regime of hydraulic expansion is the optimum regime for qualitative sealing cover formation.

Another regime of sealing is free flow of grout. With a free flow regime propagation of grout is not elastic, because the grout internal pressure is less than the normal confining stress acting on the fracture walls. So the mechanical effect of grout influence upon the rock is not essential. Fracture voidage is partly sealed, so initial permeability is reduced. During this regime sealing of big tectonic fractures and joints or zones of anomalous high permeability takes place.

Finally, when grout is propagating through the medium with low resistance it may come out to overlying horizons, so the quality of sealing will be low.

Apparatus and software package

Emplacement of sealing grout curtain around the open pit (diamond pipe 'MIR" in Yakutia) was developed by Production Association SPETSTAMPONAZHGEOLOGIA. Water-bearing layers were located at a depth 300 - 500 m. Injection wells were drilled around the pit.

A control station registering injection pressure, flow rate, clay grout density and the quantity of grout, was used to monitor the process of grout injection. All these parameters were transferred to an electronic device ARS connected with a personal computer. Software packages included the following programs: ARS (experimental data treatment, mathematical treatment of received information), GROUT (data base for current work containing grout injection parameters received from ARS as well as technological, physical and geomechanical data), WALL (data base containing profiles and coordinates of boreholes and results of sealing curtain creation), WALL-GR (graphics view of sealing curtain). At any stage of the injection process programs ARS and GROUT interpret all the obtained information, diagnose the grout propagation regime, determine the dimensions of grout propagation and estimate the quality of sealing. Thus optimum control of the grouting process is achieved.

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