Simulation of propagation of leachate after the ISL mining closure

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Abstract. The solution formed in the process of uranium in-situ leaching propagates after the mining closure with the regional groundwater flow. Forecasting the migration of solution requires account of chemical reactions in the system of the acid solution and subsurface medium. The process of propagation of solution, and methods for this process modeling are considered in the paper. The Eulerian approach to calculation of reactions leads in the present case to significant numeral dispersion. In order to avoid this numerical effect, we have solved two independent passive mass transport problems. The final solution is a geometrical intersection of passive solutions.

Introduction

The forecast of propagation of leaching solutions is the important part of assessment of potential impacts of uranium in-situ leaching. This paper presents the model results of migration of leachate for one of the uranium in-situ leaching sites. The goal includes forecasting the migration of leachate, and assessing risks of pollution of groundwater used for water supply. An aquifer system within the study area consists of several layers. Uranium ore is deposited in the lower aquifers at a depth of near 500*m* from the land surface. The upper aquifers are used for groundwater supply. The ISL operational scheme of studied mining plant consists of injecting and pumping well rows, and sulfuric acid is used as a leaching liquid.

The territory has an area of about 150 square kilometers. Size of a model grid cell used for the forecasting simulation is 50x50*m*. The aquifer system was divided into 9 model layers. Taking into account hydrodynamic dispersion for the mass transport modeling brings insignificant corrections to the resulting area of solution distribution in the present case. So dispersion was not accounted for.

Sulfuric acid not only provides chemical conditions for uranium dissolution, but also reacts with the subsurface medium, mostly with the carbonate minerals. Products of these reactions that appear in the solution are mainly calcium, magnesium, and sodium sulfates. A domain of high acid and sulfate concentration is formed in the process of leaching, and its size is close to the size of uranium ore deposit. A domain filled with sulfates has larger size than the domain filled with acid. Besides that, the total sorption of sulfates requires more time than the total acid neutralization. As an example, we consider only the propagation of acid solution.

Description of the process

It is supposed that all reactions proceed relatively fast compared to the groundwater flow, and the local equilibrium assumption is valid. The neutralization of acid provided by reactions with the medium results in a transition of uranium and other elements from the solution to solid phase. Thus the process of acid neutralization results in retardation of propagation of acid front in relation to the propagation of “clear” water.

Let determine a retardation factor for the leachate. Suppose that capacity of sorption E is a constant, which depends on the content of acid sorbing minerals in the subsurface medium. Balance equation for an elementary element dl, containing acid in the porous space, and acid spent for the reaction over dt time interval, can be written as follows:

$$(n\,C+\rho\,E)\,F\,dl=Q\,dt\,C\,,\qquad Q=v\,F\,, \tag{1}$$

where the variables are defined as follows: C, concentration of acid in solution [ML-3]; n, porosity [-]; E, capacity of sorption [MM-1]; ρ, bulk density of subsurface medium [ML-3]; F , cross section of the element; Q, Darcy flow rate [L3T-1]; v/n, seepage velocity.

Velocity of the acid front can be obtained from (1) as follows:

$$\frac{dl}{dt}=\frac{v}{(n+\rho\,E/C)} \tag{2}$$

Hence the retardation factor is

$$R=1+\frac{\rho\,E}{n\,C} \tag{3}$$

As a result of field and numerous laboratory tests and simulation of pilot leaching, the average retardation factor for the territory had been taken equal to $R_0=10$.

The acid solution extends in all directions from the system of technological wells, while the mining is proceeding. This is provided by pumping wells, which lift the leachate on the surface for further processing, and is not an assumption in our case. Modeling results show that presence of the natural regional groundwater flow practically has not an influence on directions of transport of leachate, and that we deal with a single front between natural water and the leachate.

The situation after the mining closure is another one. When technological injecting and pumping wells are stopped, the propagation of leachate's remainder is completely determined by the regional groundwater flow. Thus two fronts appear. A forward front is a front where the solution reacts with the medium. A back front is a front where the leachate is displaced by natural water. Velocities of these fronts are different.

We suppose that processes of neutralization are irreversible. This means that neutralization processes proceed only at the forward front. Therefore the forward front of the solution propagates with the velocity, which is determined by the appropriate retardation factor. The back front of the solution propagates with the same velocity as "clear" natural water. The retardation factor for the back front is equal to 1.0 for all components. So we need to model two liquids together, the only one interacting with the subsurface medium.

Test of the Eulerian approach to reaction calculating

There are numerous different Eulerian-Lagrangian methods that made it possible to model mass transport and chemical reactions in groundwater systems (Zheng and Wang (1999); Clement (1997); Prommer et al. (2003)). It is noteworthy that the Eulerian approach involved the use of the concentration averaged over the whole cell of the model grid, rather than the "natural" concentration in some concrete point of the space. A particular method for calculation of concentration may vary, but values obtained as a result of calculation approximately correspond to the relative volume of component in the grid cell.

Consider 1D groundwater flow where one liquid, with relative concentration $C_0 = 1.0$, displaces another liquid with zero concentration. The first liquid reacts with the medium. The reaction mechanism, for example, is the same as for the acid-medium reaction in our leachate, when the retardation factor is in inverse proportion to the concentration of solution:

$$R = 1 + \frac{A}{C}, \tag{4}$$

where C is a relative concentration of displacing solution, A is a time independent constant.

The distance of propagation of displacing front at the time moment ΔT equals to

$$\Delta L = \frac{v\,\Delta T}{n\,R_0} \tag{5}$$

Let ΔL be a spatial step of 1D model grid. Then we will simulate the propagation of solution by using equations (3) and (5). Divide a time interval ΔT onto m

equal time steps Δt:
$\Delta T = m\,\Delta t$

The distance, which is passed by the solution during the one time step, equals to:

$$\Delta x_i = \frac{v\,\Delta t}{n\,R_{i-1}} \;,$$

where R_{i-1} is a current value of the retardation factor calculated by equation (4), by using the value of "concentration" from the previous time step.

After the i-th time step, the calculated "concentration" of displacing solution equals to:

$$C_i = \frac{\sum_{i=1}^{m} \Delta x_i}{\Delta L} = \left[\sum_{i=1}^{m} \frac{1}{R_{i-1}} \right] \frac{R^0}{m} \tag{6}$$

Thus we obtain an absurd result: the distance passed by the displacing solution depends on the modeling time discretization.

Check the result of modeling using equations (4) and (6). When $m = 1$, the result is exact. However, when m equals to any other value, the situation is changing. Let, for example, $m = 2$ and $A = 9$, where A is the constant from equation (4). Suppose that before the first time step displacing solution locates in the previous model cell, and the retardation factor for displacing solution initially equals to $R_0 = 10$. The results of this numerical "modeling" are presented in the table (Table 1). We have obtained the wrong result. Displacing solution has left the model cell in 3rd time step instead of 2nd time step as it follows from equation (5).

Test these numerical effect ones more. The results of calculation, when $m = 5$, are presented in the table (Table 2). The result is wrong again. Displacing solution has left the model cell in the 10th time step instead of the 5th time step as it follows from equation (5).

It is not difficult to show that numerical errors don't reduce, when time steps decrease, and even become increasing and accumulating. The solution propagates with variable velocities since the model "concentration" is calculated in each time step, and different in each time step. The retardation factor, in this case, equals to its real value only in the first time step, and greater in any further steps. Thus the time of solution leaving from the cell is determined by some average value, which is always greater than the real value of the retardation factor. Note that the considered example can be extended for any other reaction process described by concentrations, and numerical effects have also the same nature for other processes.

Thus the Eulerian approach can cause significant numerical errors that increase when time steps decrease. The alternative for the Eulerian approach is a pure Lagrangian approach to mass transport modeling, for example, similar to one of the methods described in Batycky (1997), Thiele et al. (1995), Thiele (2001). We used another method proceeding from requirements of the following expertise. The method uses the only advection part of widely distributed MT3DMS code described in the next section.

Solution method

Since the reaction process is irreversible, it proceeds only at the forward front. The solution doesn’t interact with the medium upstream from the forward front, since the solution and medium are in the equilibrium there. Thus the medium, where the solution propagates, can be divided into two zones by the forward front of the solution (Fig.1a):

1) The active medium zone located downstream from the forward front of the solution
2) The passive medium zone located upstream from the forward front of the solution

For simulation of migration of this solution, the following approach can be used. Two mass transport problems are solved. Transport parameters of the subsurface medium are uniform in both problems. In the first problem, the transport of the active solution is modeled. The retardation factor is identical for the whole space, and equals to the retardation factor for the studied component of the solution. In the second problem, the propagation of the passive tracer is modeled. The retardation factor in this case is also identical for the whole space, and equals to 1.0. Thus

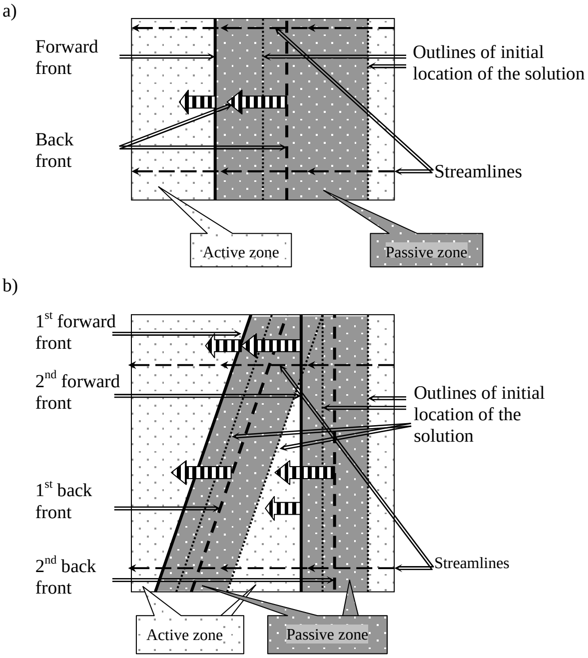


Fig. 1. Scheme of propagation of the active solution in groundwater flow. a) – simple configuration of the area filled with the solution. b) – curved area filled with the solution.

we have two areas filled with the solution:

1) Area of spreading of the active solution, which interacts with the medium
2) Area of spreading of the passive solution, which doesn't interact with the medium
3) The final solution is found by intersection of the two areas (shared part of the areas 1. and 2.).

The considered technique is correct, if and only if any streamline traverses the solution area only once. This assumption is valid for many cases, but a part of orebodies of the studied deposit is curved, and some streamlines traverse the area of the solution twice. This means that while the solution is propagating, two forward and two back fronts are formed, and the active medium zone locates not only upstream, but also downstream from one of the forward fronts (Fig.1b).

The second forward front initially propagates in the active medium zone, but in some time it will locate in the passive medium zone, which has been formed by the first forward front (Fig.1b). Since the active solution has already reacted with the medium in this zone, a new front doesn't react there. Hence the second forward front of the solution propagates in this zone with the same velocity as a passive tracer. So our scheme requires correction to this situation.

The way out of the situation is simple, but requires manual intervention. The passive medium zone can be periodically extended according as the forward front of the solution is propagating. It should be done when the back front has come near the previous boundary between the active and passive media. In our case study, we had to correct the passive and active zone boundaries only twice.

Table 1. Results of test mass transport calculation, when m=2.

Step	R_i	C_i
1	10.00	0.500
2	19.00	0.763
3	12.79	<1.0

Table 2. Results of test mass transport calculation, when m=5.

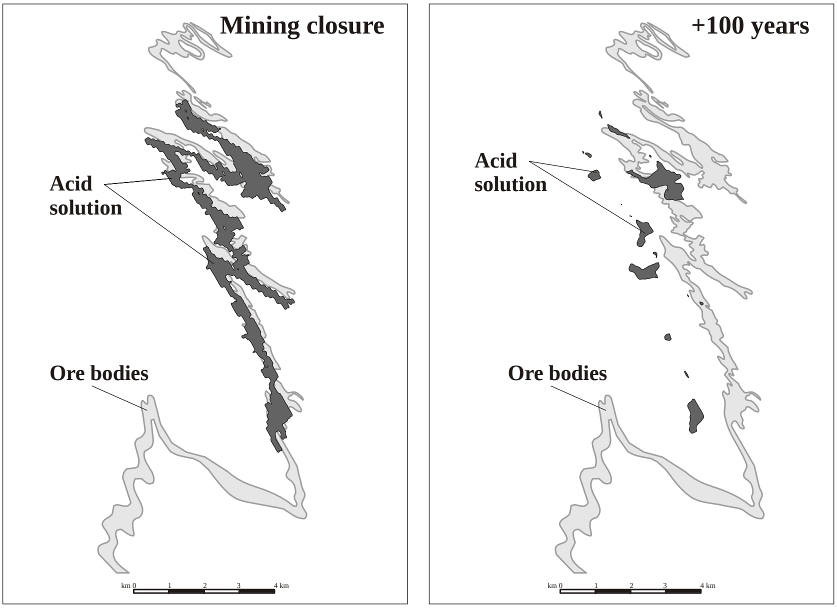
Step	R_i	C_i
1	10.00	0.200
2	46.00	0.243
3	37.96	0.296
4.	31.39	0.360
5	26.01	0.437
6	21.60	0.529
7	18.00	0.640
8	15.05	0.773
9	12.64	0.932
10	10.66	> 1.0

Results

By having used the method described, the model forecast of propagation of leachate was done for mining and after mining time. The flow problem was solved by Chebyshev’s chess algorithm from the ModTech suite, and the MT3DMS code was used for the mass transport modeling.

Outlines of uranium ore bodies and zones filled with the leachate are shown in Fig.2 for one of the model layers. Fig.2a contains the spreading area of the leachate at the moment of mining closure. Configuration of the leachate area is close to configuration of the ore bodies. An area of the solution, which would have spread in 100 years from the moment of the mining closure, is shown in Fig.2b. Area filled with the solution is significantly smaller in this case.

Model results show that time required for the total neutralization of the acid is near of 370 years. The maximum distance of propagation of solutions is near of 700-800*m*. In spite of relatively significant time required for acid neutralization at the considered deposit, practically there is no risk of contamination of groundwater used for water supply by the leachate. Only the upper layers are used for water supply at the territory, and uranium ore bodies locate significantly deeper. Even at the moment of maximum size of areas filled with the solution, solution locates deeper than groundwater used for water supply, and doesn’t affect the upper aquifers.



a) **b)**

Fig. 2. Spreading of the leachate at the moment of mining closure a) and 100 years after mining closure b).

Conclusion

Simulation of propagation of leachate during and after the uranium in-situ leaching is considered in the paper. During the mining, the leachate extends in all directions from the system of technological wells. Regional groundwater flows have low influence on the initial zone filled with the leachate. After the mining closure, when all technological wells are stopped, a zone filled with the leachate propagates with the regional groundwater flow. The size of the zone decreases by interaction of the active components with the subsurface medium.

There are various numerical methods that made it possible to model propagation of the reactive solution in the groundwater flow. Some of the methods use the Eulerian approach to reaction calculating. In the considered case, the Eulerian approach leads to significant numerical dispersion. Conjugation of solutions of two passive mass transport problems was used in order to reduce errors caused by numerical dispersion. Propagation of an active solution is modeled in the first problem. The second problem considers the propagation of a passive tracer that doesn't interact with the medium. Parameters of the transport are the same for two problems, except for the retardation factor. So two areas filled with the active and passive solution are formed. The final solution is found as intersection of these two areas.

The model forecast shows that the maximum distance of propagation of leachate does not exceed 700-800*m*. The total time of the forecast is 400 years. Results show that the total neutralization of acid should occur during this time. In spite of relatively significant time required for the neutralization of acid, there is no risk of contamination of groundwater used for water supply. This is conditioned by deep occurrence of the uranium ores deposit.

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