SOIL MODIFICATION METHOD IN THE BORDER ZONES OF SURFACE-TYPE STORAGE FACILITIES AND EXPERIENCE OF ITS APPLICATION

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Federal State Unitary Enterprise RADON has considerable experience in the implementation of the soil modification process at surface-type storage facilities. The modification process involves modifying solution injection performed under pressure through a system of process wells into the rocks of the border zone. Upon penetrating into the rocks, the solution interacts with them reducing their hydraulic permeability, which eliminates the risk of radionuclide release into the environment and increases the efficiency of the natural barrier. The report presents the results of an overview discussing available soil modification methods, evaluates laboratory and pilot-industrial research and recommendations on the selection of a promising modifier for the modification of border zones around storage facilities operated at FSUE RADON's industrial site.

Keywords: *radioactive waste, soil modification, surface-type storage facilities, process wells, modifying solution, hydraulic permeability.*

Since the 1960s, historical surface-type storage facilities (SSF) have been operated by FSUE RADON at the site of the Sergiev-Posad's Scientific & Industrial Complex (hereinafter referred to as SIC) holding a large inventory of solid intermediate- and low-level waste (RW). Structurally, these are reservoirs made of monolithic or prefabricated reinforced concrete buried to a depth of 4—4.5 meters into the surface clay soil. Multiple engineered safety barriers (EBS) and a natural safety barrier constituting of rocks both directly adjacent to the storage facility (the border zone) and the host rock mass itself provide the environmental safety of the storage facilities.

At the operational stage, due to increasing hydraulic permeability of the safety barriers, the safety system affected by certain temporal, natural and technogenic factors gradually loses its protective properties. Thus, the nature of radionuclide transport processes occurring both inside and outside the storage facilities changes and their intensity increases, which, in a real time, may adversely impact their performance in terms of the environmental safety.

Facility-level soil monitoring program (FLSM) being implemented at the SIC site shows that the natural barrier has been playing a vital role in the environmental safety system all through the SF operation: it's the last one at the forefront of the environment which is able to act effectively in any emergency situations associated with the EBS.

Natural barrier is a rock mass constituting of backfill soils filling the gaps between the walls of the storage facility and the pit arranged during SSF construction. These soils have high hydraulic permeability factor of up to 1 m/day, whereas in case of undisturbed loamy soil, corresponding to the typical rocks constituting to the SSF site, this factor accounts for thousandths of the given value.

Natural barriers refer to renewable elements of the SSF's environmental protection system: their timely remediation prevents the outgrowth of storage reliability deficiency impeding radionuclide releases into the environment, which, in turn, ensures safe operation for this storage facility type.

Modern remediation methods have been evaluated. The study showed that given the SSF siting conditions and the soils constituting to the natural safety SSF barrier, in particular, soil modification could be considered as a most promising remediation option.

Relevant methods have been evaluated with two of them found to be most commonly applied both in Russia and abroad: with and without soil mass destruction [1]—[8], [10]—[16].

The one involving soil mass destruction provides for soil mass loosening and its mixing with a modifying solution. However, in case of soils contaminated with radionuclides this method yields large amounts of low- and very low-level waste generated due to soil mass loosening and dilution and requiring further disposal, which is seen as its main disadvantage.

The method providing for no soil mass destruction involves the modifying solution injection into the soil massif through a well system. The composition penetrating the soils interacts with them reducing their hydraulic permeability, thereby, preventing possible radionuclide releases into the environment and increasing the natural barrier's efficiency. In this case soil mass remains intact, thus, higher environmental safety level can be achieved during work execution; secondary RW streams requiring further disposal are avoided and the labor intensity decreases. Given these advantages, this method can be considered as the preferred one for natural safety barrier remediation.

According to current global experience, four rock mass strengthening methods are basically used in industry and mining: cementation, claying, silicification and tarring.

Relevant goals, results and conditions associated with the above methods have been evaluated. Several reasons impeding their application under SSF conditions have been identified, namely: insufficiently small particle size of the solid phase in the solutions, their high viscosity and the occurring physicochemical process (hardening) having great impact both on the solution injection process and the solution interaction and distribution in the modified soils. Thus, process solutions applicable under the SSF conditions should:

- have a sufficiently small particle size of the solid phase providing deep solution penetration into soils;
- have low viscosity;
- avoid physical and chemical processes that may have considerable impact on the solution injection;
- effectively reduce the hydraulic permeability of soils within the solution penetration zone;
- produce no destructive effect on other safety barriers;
- be available at an adequately low cost.

A study focused on modifiers currently added as fillers to process solutions showed that these requirements were best met by certain types of polymer dispersions. Therefore, by the time of our research, the LBS modifier developed in the US by Enviroseal Corporation, produced under its license in Russia and available at a cost of about 12 US dollars per liter could be considered as the best option in terms of its efficiency and compliance with the above requirements.

This modifier is a silicon polymer dispersion, which is a low-viscosity liquid applied in road construction to improve clay soils (loams and clays) in terms of their physical and mechanical properties.

Seeking to provide the environmental safety at the SSF site, SIC management launched a project on the development of a soil modification method to treat the soils constituting to the natural barrier in the border zone of the historical storage facilities. Under the project involving a series of laboratory studies and pilot tests, the LBS modifier was adopted as the basic one.

Laboratory research was seeking to assess the feasibility and effectiveness of the soil modification process considering the SSF siting conditions, to evaluate optimal modifier concentration in the solution, as well as the parameters and characteristics of the resulting soil. The experiments were implemented at a purposely developed laboratory unit — a physical model representing the modification process able to simulate both the process of the modifying solution injection into the process wells and the process of modifier interaction with the soil (Figure 1). The laboratory unit involved the following elements: measuring tank (1); flow column (2); injection line (3); hydropneumatic pump (4) consisting of a casing (5), a pressure relief valve (6), an air pump (7) and a pressure gauge (8).

The flow column consisted of a metal case with interconnected separate sections (pipes).

In the experiment, it was filled with loam common for the SSF site and saturated with water by pumping. During the injection process, the flow rate

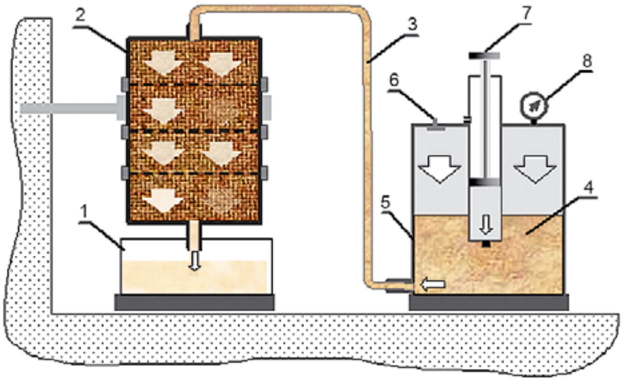

Figure 1. Layout of the laboratory unit

and the water pressure were measured to calculate the preliminary (initial) hydraulic permeability of the sample. After the loam got saturated, the water was pumped out from the flow-test column: it was filled with a modifying solution injected through the sample. Based on this process, the total hydraulic permeability factor of the modified loam sample was calculated. Then the flow-test column was disassembled into sections and the water was pumped through each section: the results obtained were used to calculate the hydraulic permeability of soil in each section.

Based on this algorithm, one could calculate the size of the zone with decreased hydraulic soil permeability and to explore the degree of its changes depending on the size of the zone, as well as to evaluate how the modifier concentration in the process solution could affect these indicators.

Its optimal concentration has been calculated based on a comparative assessment of all previous results.

The calculated efficiency of the LBS-based modifying solution accounted for a concentration range of 25—1,000 cm^3/l. The study revealed a dependence between the effectiveness of the LBS modifying solution and the concentration of the modifier in it (Table 1).

Table 1. Dependence between the effectiveness of the LBS-based modifying solution and the concentration of the modifier in the solution (1 liter of modifier costs 900 rubles)

Modifier concentration in the solution, cm^3/l	Radius of the zone with decreased hydraulic permeability, m	Degree of hydraulic permeability reduction	Cost per 1 m^3 of the solution, rubles
25	0.5	483	22,500
100	0.6	1,115	90,000
150	0.85	3,110	135,000
250	0.45	881	225,000
1,000	0.3	128	900,000

Data from Table 1 show that increased concentration of the modifier in the solution boosters its efficiency reaching its maximum at a concentration of 150 cm^3/l; while further increase in the concentration, decreases the solution efficiency.

Therefore, this concentration appears to be optimal, since, at a relatively low cost (per 1 m^3 of the solution), it provides the biggest radius of the zone and most effectively reduces the hydraulic soil permeability. For this reason, LBS soil modifier solution with a concentration of 150 l/m^3 has been recommended for further pilot studies on soil modification at the SSF site.

Pilot testing was implemented in the border zone of a historical solid waste storage facility at the SSF site. It was launched to prove the effectiveness of the modification process and to develop its application methods considering the SSF conditions.

Process wells were spaced 1 m apart along the contour of the selected site. The number of wells was calculated based on the size of the area subject to modification. Figure 2 presents relevant designs and equipment layout. Cement retainer was used to seal the gaps at the wellhead (4). The wells were drilled by auger to a depth of ~6 m.

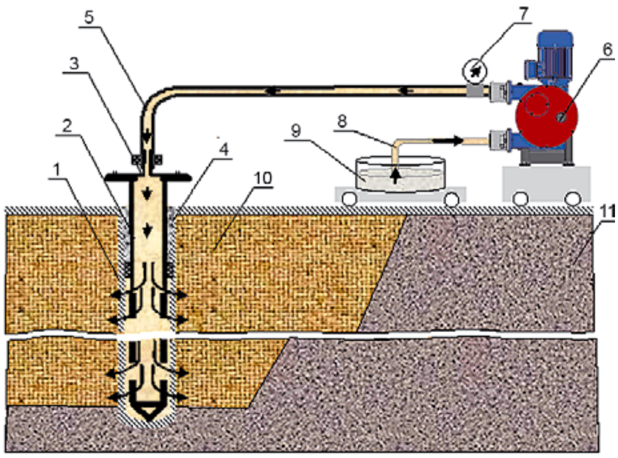

Figure 2. Well designs and equipment layout:

1 — process well; 2 — pipe with slotted filter and a flange;
3 — branch pipe with a flange; 4 — insulating retainer;
5 — delivery hose; 6 — pump; 7 — pressure gauge;
8 — suction hose; 9 — tank with the modifying solution;
10 — modified soil; 11 — soils of the host mass

Hydraulic permeability of the soils was measured based on the express injections into the process wells implemented in two stages: in the initial state (before the modifying solution was injected into them) and 120 hours after. Express injections were implemented according to the method developed by R. M. Shestakov [9].

Table 2 summarizes the pilot testing findings and the evaluated effectiveness of the LBS modifier.

Table 2. Pilot testing findings and evaluation of the LBS modifier effectiveness with an optimal concentration of 150 l/m³

Hydraulic permeability factor, m/day		Reduction degree K_f	Radius of the HP reduction zone K_f, m	Cost of the modifier, rub/l	Cost per 1 m³ of the solution, rub	Degree of HP reduction K_f	
Pre-modification stage	Post-modification stage					Laboratory studies	Pilot-industrial studies
$1.53 \cdot 10^{-2}$	$5.8 \cdot 10^{-5}$	264	0.85	900	135,000	3,110	264

The following conclusions could be drawn based on the above analysis:
- feasibility and efficiency of soil modification in the border zones of near-surface RW storage facilities using process LBS modifier solution have been demonstrated;
- the proposed process well layout has increased the efficiency of the natural barrier contributing to the environmental safety of SSF operation.

The results presented in Table 2 show that laboratory research seems to slightly overestimate the decrease in the hydraulic soil permeability as compared to the pilot testing, which is explained by the high complexity of the hydrogeological conditions inherent to the natural soil mass as compared to the physical model used in the laboratory studies.

Present study shows that the process LBS modifier solution can be considered effective and provides an optimal result, but nevertheless its cost is quite high due to the high cost of the modifier itself.

Modern market analysis showed that a Russian company SOFEX-Silicon LLC producing a polymer hydrophobic organosilicon liquid GKZH-11N grade A was selling it at about 12 times lower price than the previously studied LBS modifier. Moreover, preliminary laboratory studies have revealed similarity of these two products according to their characteristics. Thus, to optimize the final result according to the price-quality criterion, the intended goal can be achieved at much lower costs if the GKZH-11N grade A is applied as a modifier.

Moreover, in case if a modifier involving imported components (LBS) is replaced by a Russian analogue (GKZH-11N) some important risks are eliminated, namely, those associated with logistics and shortages of the required materials promoting wider application of this method.

Conclusions

The study focuses on the application of soil modification method in the border zones of near-surface storage facilities. It also overviews the existing methods applied to reduce the hydraulic soil permeability. Based on the study, a modifier most fully complying with the appropriate requirements has been selected; the implemented laboratory and pilot tests have validated the feasibility and the effectiveness of the proposed solutions when applied to improve the natural barrier's efficiency at near-surface storage facilities. A promising modifier considerably reducing the cost associated with soil modification process has been recommended as well. Based on the implemented laboratory studies and the pilot testing:

1) the prospects of the soil modification method causing no disturbance to the natural soil mass have been clearly demonstrated as regards the improved efficiency of the natural safety barriers exposed to the natural soils and designed to provide the containment of radioactive and other environmentally hazardous substances;

2) findings of the laboratory studies and the pilot testing were found to have a fairly high degree of convergence and, assuming due application of the proportionality coefficient, can be recommended to forecast the decreasing degree of hydraulic soil permeability under pilot studies;

3) a process solution based on LBS polymeric soil modifier at an optimal concentration of 150 l/m³ was found to have the highest efficiency; however, its unit cost (per 1 m³) appeared to be quite high due to the high cost of the modifier itself;

4) it has been established that a Russian company produces a polymer hydrophobic organosilicon liquid GKZH-11N grade A at a cost being about 12 times lower than the one of the LBS modifier that meets the requirements set forth for the process solutions used to modify soils under RW storage facility conditions;

5) hydrogeological studies focused on the storage facilities operated at the SSF site showed that the hydraulic permeability of soils at each storage facility site differs in a quite considerable way; each facility is characterized with some particular features. Therefore, a series of ad hoc studies should be launched to evaluate each site where soil modification is planned;

6) it has been demonstrated that the developed method could be used to provide the containment of individual soil mass areas contaminated not only with radionuclides, but also with other environmentally hazardous substances.

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