Secure Systems Design and Technology Development. Veliko Tarnovo, Bulgaria
Proceedings of the International Scientific Conference, 2026. Volume I, 297-301

Reduction of the Specific Activity of Radioactively Contaminated Soil Using the High-Pressure Hydro-Cleaning Method

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***Abstract* — Radionuclides are mainly bound within soil layers and exist in the Earth's crust as mineral-like substances that are resistant to heat and electrical воздействия and can split into thin layers, making them difficult to wash out easily. Therefore, in order to extract radionuclides from radiation-contaminated soil layers and reduce their specific activity, it is necessary to separate them using various processing methods. Currently, conventional methods developed for treating radiation-contaminated soils include extraction using acids, alkalis, or other chemical reagents. These treatment methods require large amounts of chemical reagents, making them economically inefficient and difficult to apply to large volumes of contaminated soil.**

Keywords* — *radioactive soil, radionuclides, soil decontamination, high-pressure hydro-cleaning, specific activity reduction, radiation contamination, soil remediation, hydro-mechanical treatment, environmental safety, gamma spectrometry.

I. INTRODUCTION

Radioactively contaminated soils represent a significant environmental and industrial safety challenge in modern conditions. This issue is particularly critical in mining and industrial areas, where radionuclides accumulate within soil layers and pose serious risks to both the environment and human health. Radionuclides are typically strongly bound to fine soil fractions, making their removal by conventional washing methods difficult.

Traditional treatment methods, including extraction using acids and alkalis, are widely used; however, they require large amounts of chemical reagents and are economically inefficient. Moreover, these methods present environmental and technological limitations when applied to large volumes of contaminated soil.

Therefore, the development of efficient, cost-effective, and environmentally safe technologies for reducing the specific activity of contaminated soils is of great importance. This study investigates the application of a high-pressure hydro-cleaning method combined with soil dispersion and fractionation processes to separate radionuclides and reduce their concentration. The proposed technology minimizes the use of chemical reagents and improves the efficiency of soil remediation.

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II. MATERIALS AND METHODS

To conduct the research, when studying the spatial and depth distribution, a regular sampling grid is established in

Online ISSN 3044-7771
https://doi.org/10.68302/std2026.vol1.194

radionuclide-contaminated soil areas at intervals of 25–30 meters in the horizontal direction (along the X and Y axes). Samples are collected both at the contamination center and within a radius of 5–30 meters. This approach allows for a detailed assessment of variations in activity levels.

The distribution of activity with depth is determined by sequential sampling of soil layers at 15 cm intervals down to a depth of 0.8 meters. Experimental results indicate that radionuclide activity significantly decreases with increasing depth. Monitoring is carried out at four key time points: before treatment, immediately after treatment, and after 6 months and 1 year. This method makes it possible to evaluate both the immediate effectiveness of the technology and the long-term dynamics of changes in the radiation background [1-7].

High-resolution gamma spectrometers are used to quantitatively determine the concentrations of radium, potassium, and thorium. In addition, the granulometric composition and organic matter content, which influence radionuclide binding, are also analyzed [15-20].

In this study, a new technology aimed at reducing the volume of contaminated soil was applied by using a high-pressure washing method for the treatment of soils contaminated with radioactive elements. The implemented technology reduces processing costs by 15–20% compared to previously used high-temperature treatment (sublimation) methods and chemical extraction technologies [21-24].

In this technology, a dispersant is added to the contaminated soil, after which it is continuously disintegrated using a high-pressure flow of 4 MPa or higher. As a result, minerals that have adsorbed radioactive elements are separated from the aggregated soil and recovered, thereby partially neutralizing and reducing the volume of contaminated soil. The dispersant reduces the zeta potential of the aggregated soil, ensuring stable dispersion of fine soil particles and facilitating the separation process [8-12].

This process consists of the following main stages:

The first stage involves soil preparation, in which contaminated soil is mixed with water and dispersants and then fed into the soil supply unit. At this stage, solid particles in the soil are thoroughly mixed and prepared for subsequent technological processing. Uniform distribution of soil particles and effective mixing with dispersants improve the efficiency of the washing process [25,26].

The prepared mixture is delivered to the washing ejector using a high-pressure pump. The pump pressure is at least 4 MPa, which enables high-pressure washing of the soil and physical separation of particles. Through high-pressure washing, the ejector separates fine soil particles (<100 μm), thereby ensuring a reduction in contamination through physical means [27,28].

At this stage, layered and fine soil fractions are separated and directed to the sedimentation process for particle settling, where special reagents are added. These reagents promote the aggregation and settling of fine and layered particles, which plays a crucial role in reducing radioactive contamination. This process also serves to optimize the particle size distribution within the resulting sediment [29, 30].

The settled soil is then passed through a dewatering unit, where excess water is removed. As a result, the processed soil is divided into particle size fractions: washed soil (20–100 μm) and layered soil (<20 μm). In the final stage, the dewatered soil is discharged via a vibrating screw conveyor and prepared for further processing or disposal [12-15].

As a result of this technological process, the level of soil contamination is significantly reduced, fine and layered particles are effectively separated, and radiation safety is ensured through sedimentation with reagents. Furthermore, the resulting soil is dried and stabilized, which reduces radiation and chemical exposure risks for workers and allows for environmentally safe and sustainable reuse.

III. Results and Discussion

Figure 1 illustrates the process of separating hazardous radioactive substances through the dispersion and fractionation of soil composition. At this stage, soil aggregates are broken down into fine particles, allowing fractions bound with radioactive substances to become free. Subsequently, high-pressure washing and fractionation processes are carried out, resulting in the separation of coarse soil particles and fine fractions containing radioactive materials.

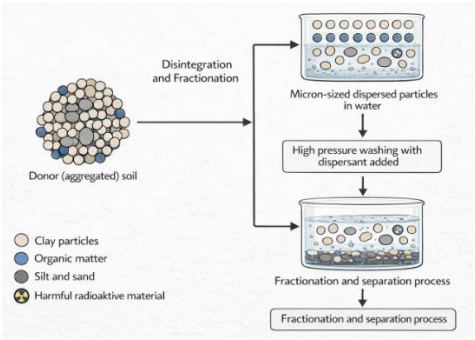

Fig. 1. Method for separating hazardous radioactive substances through dispersion and fractionation of soil composition.

The structure of the ejector used as a soil washing device is shown in Figure 2.

This device draws soil into a pipe with a diameter of approximately 50 mm and washes it using turbulent flows generated by a high-pressure stream. The addition of a dispersant under highly turbulent conditions produces an effective disintegration effect.

In this system, the contaminated soil, disintegrated by high-pressure washing, undergoes subsequent classification and separation processes, during which minerals that have adsorbed radioactive elements are selectively separated. The soil is then divided into washed soil and concentrated fractions, followed by dewatering.

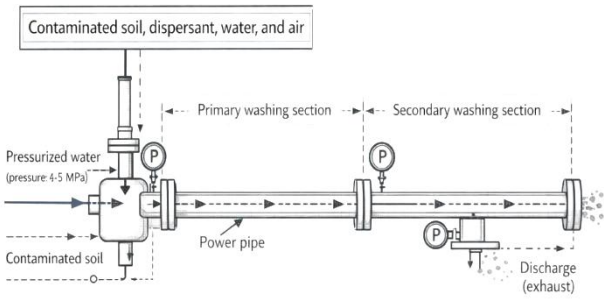

Fig. 2. Method for separating hazardous radioactive substances through dispersion and fractionation of soil composition.

The system shown in Figure 1 utilizes a vibrating screen, a screw conveyor, and a wet cyclone as classification devices.

Fig. 3. Photograph of a high-pressure cleaner (ejector).

For the experimental studies, soil samples were primarily collected from uranium geological exploration and extraction sites. Contaminated soils with radionuclide concentrations ranging from 7,500 to 41,700 Bq/kg were selected.

After the washing process, an increase in particle dispersion and partial surface cleaning is observed. In the case of enriched soil, the separation of fine fractions and the accumulation of active components in certain portions become evident.

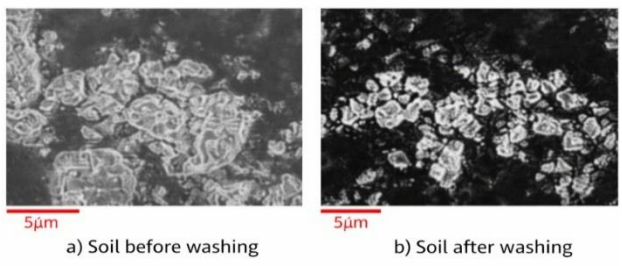

Fig. 4. SEM (Scanning Electron Microscopy) image of soil washed under high pressure.

The obtained results demonstrate the effectiveness of soil washing and enrichment technology and confirm that it meets occupational safety and sanitary requirements in the remediation of radiation-contaminated areas.

Figure 5 shows the recovery rate of soil particles. The developed system demonstrated a recovery efficiency of 47–75% for soil particles with a size of less than 20 μm and 74–91% for particles with a size of 20 μm and larger.

These results indicate the effectiveness of the developed system in soil disintegration, particle classification, and recovery processes.

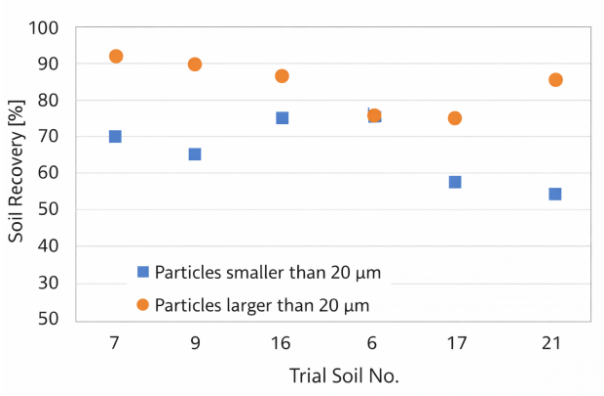

Figure 5. Recovery rate of soil particles

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IV. CONCLUSION

The results of the conducted studies showed that the radiation condition of soil in workplaces of mining industry enterprises represents a significant risk factor for workers' health. During the study, it was determined that the specific activity of radioactive substances in soil initially varied within the range of 7,500–41,700 Bq/kg, with an average value of 15,800 Bq/kg. These values are considered high for industrial conditions and affect both external gamma radiation exposure and internal exposure through soil.

As a result of applying the proposed technology based on high-pressure washing and fractional separation, the concentration of radioactive substances in the soil decreased to 2,200–5,200 Bq/kg, with an average specific activity of 3,800 Bq/kg. This corresponds to an average reduction of about 76% compared to the initial condition, significantly lowering the radiation hazard level of the soil.

The reduction in soil activity was also reflected in the radiation doses received by workers. Before treatment, the annual external gamma radiation dose ranged from 0.8 to 1.8 mSv/year, while after treatment it decreased to 0.5–1.1 mSv/year, representing a reduction of approximately 1.4–1.7 times. Similarly, the internal radiation dose due to dust inhalation decreased from 0.4–0.9 mSv/year to 0.25–0.55 mSv/year, corresponding to a reduction of about 1.5–1.6 times.

As a result, the total annual effective dose received by workers decreased from an initial range of 1.2–2.7 mSv/year to 0.75–1.65 mSv/year after treatment. These values are significantly lower than the permissible limit of

20 mSv/year established by regulatory standards, indicating a low level of radiation risk to workers' health.

Thus, the proposed soil treatment methodology enables effective control of radiation risk factors in mining enterprises, reduces occupational radiation exposure, and improves working conditions. The obtained results confirm the practical significance of this technology within radiation safety systems and scientifically justify its implementation in industrial applications.

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