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Microbial Activity Within the Earth Dam: Consequences and the Suppression Strategy

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Abstract

We studied some geochemical parameters at the earth dam of the Kama River water reservoirs, Russian Federation. The dam's body consisted of sand-gravel soil, alluvial and peat-bearing lacustrine marsh sediments were disposed at its basement. The system of vertical and horizontal drains mounted within dam's body withdrew filtering river water to reduce hydrostatic loading on the dam. Changes of cation and anion content of filtering river water, gas content of subsurface air, and mineral content of the dam's material were measured. Some indications of suffosion process were detected. We hypothesize that microorganisms living within the dam's body use river-water dissolved organic matter in their metabolism, and thus influence these changes. We hypothesize also that the rise of organic matter content in river water could lead to the intensification of microflora's activity, which in turn could lead to dangerous circumstances, such as weakening or failure of the dam. To avoid this situation, we studied possible techniques to suppress metabolic activity of ground's microflora. The main goal was to reduce microflora's gas-forming activity (mostly methanogenesis) as it dramatically reduces the strength of the dam. This paper describes both theoretical considerations and the results of our laboratory experiments aiming to suppress methanogenesis within the dam's body. The developed technique of methanogenesis suppression was proposed to the dam's officials.

Keywords

Earth dam • Microbial methanogenesis • Suppression

1 Introduction

Microbes take an active part in the transformation of the geological environment. The physiological peculiarities of microorganisms and their capability to act on minerals, organic and inorganic substances contribute to their considerable influence on soil and rock properties: structure, mineralogical content, bearing strength, and other parameters (Bolotina and Sergeev 1987; Kuznetsov et al. 1962; Maksimovich and Khmurchik 2012, 2013; Radina 1973).

The activity of microorganisms can change physical-mechanical properties of soils and rocks due to the following processes and factors: the formation of gases, which causes soils and rocks deconsolidation and alters their bearing strength; the leaching of the chemical elements from the rock that leads to the destruction of rock's mineral skeleton and subsequent decrease in mechanical strength of the rock; the change of microaggregate and chemical compositions of the soil, including the dispersion of clay aggregates, which increases the hydrophilicity and the deterioration of the strength and deformation properties of the soil as the result; the excretion of microbial metabolites exhibiting surface-active properties which reduce the strength of the structural bounds in the soil (Moavad et al. 1976; DeJong et al. 2006; Hendry 1993; O'Reill et al. 2005; Yang et al. 1993). Microbiological activity can considerably increase during anthropogenic influence on the soil.

So metabolic activity of microorganisms can change the geochemical parameters of soil and water and lead to undesirable consequences after the building of

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hydrotechnical constructions and during their lifespan (Koff and Kozhevina 1981; Maksimovich et al. 2001).

The aim of our study was the investigation of the dam's soil and water to reveal deviations in their characteristics caused by possible microbial activity and to develop the technique preventing the progress of potentially dangerous microbial processes to keep the stability of the dam.

2 Geologic Background

The studied dam is one of a series of dams on the Kama River located in the Russian Federation. The earth dam was constructed of sand-gravel soil via hydraulic inwash up to a height of 19 m. The basement of the dam is presented of alluvial sediments, and is up to 14–17 m in thickness. The sediments are consisted of clays, loams, sandy loams, and fine sands. Sand bands are observed in clays and loams. Sand and gravel deposits are located in the lower part of geological column. The distribution and the composition of gravel-pebble strata are not uniform. Lenses of fine sand and interlayers of clays are observed in the gravel-pebble strata, peat is presented in the strata too. Clays exhibit high physical and chemical activity and contain an elevated quantity of organic substances (up to 8%) and trace chemical elements. Drilling has shown that the dam's material located below the seepage water level has a blue-gray-to-gray hue, and is up to 8 m in overall thickness. Blue-gray, green, bluish, and mottled (ocher-blue-gray, etc.) hues are typical of soils that have undergone gleyification, which usually occurs as a result of the anaerobic microbial processes development (Perel'man 1965). The hydrological and hydrochemical conditions before and after the dam construction were described earlier (Maksimovich and Khmurchik 2015).

3 Methods

This study evaluated the microbial activity within the earth dam and assessed the risk of microbiological processes to the dam stability. The study included standard hydro-chemical analysis of water samples from the dam's body and upstream water reservoir during the main hydrological periods of year (i.e. high water level and low water level periods). Analysis of water-dissolved organic matter in these samples was made on gas chromatography–mass spectrometry system "Agilent 6890/5973N" (Agilent Technologies, Inc., USA). 48 water samples from the dam's body and 8 samples from the water reservoir were analyzed.

The gas-analyzer "Ecoprobe-5" (RS Dynamics, Czech Republic) was used to study the content of dam's subsurface air and gas content of the drain system. Subsurface gases were sampled from the depth of 0.5–0.7 m using sampling holes which were bored by auger along the central horizontal line of the dam's downstream slope at 10 m distance from each other.

Sediment of the system of vertical and horizontal drains was sieved and microscoped, and its mineralogical analysis was performed on the X-ray diffraction analyzer "D2 Phaser" (Brucker, USA).

Analysis of physical-mechanical properties of the dam's soil, and laboratory microbiological studies of dam's water and soil were done also. More proper description of probe sampling and analyzing were described earlier (Maksimovich et al. 2014).

4 Geochemical Consequences of Microbial Activity Within the Earth Dam

The chemical analysis of dam's seepage water showed that its turbidity index exceeded one of the reservoir water by more than 6 times. Precipitate from seepage water samples was ocher in color and consisted of finely dispersed mineral particles, while the solid from a reservoir water sample was of a dark-brown color and consisted primarily of flaky particles and organic debris. The seepage water precipitate was formed as a result of long-duration contact with air and represented by trivalent iron hydroxide. The source of these trivalent iron ions was the dam's soil in which the gleying process was ongoing. The gleying process, one of the most widespread processes in the saturated zone, consists in the reduction of trivalent iron to a divalent state by microorganisms with subsequent removal of iron from gleyed horizons. A typical sign of gleying process is trivalent iron hydroxide, which is formed during subsequent oxidation processes, when former gleyed horizons are exposed to oxidation (Perel'man 1965).

The chemical analysis of water samples revealed the zones of elevated distribution of NH_4^+, NO_2^-, NO_3^-, as well as Fe^{2+} ions. The zone of elevated NH_4^+ ions content roughly coincided with the zone of elevated Fe^{2+} ions content. The HCO_3^- ions content was also elevated there (see Fig. 1). The presence of spatially coincident zones of elevated NH_4^+ and Fe^{2+} ions content suggests the occurrence of microbiological processes that anaerobically decompose water-dissolved organic substances. Herewith, the source of NH_4^+ ions is an organic substance, while Fe^{2+} ions come from trivalent iron-containing minerals and rocks of the dam's material. It is known that microorganisms reductively dissolute iron(III) minerals under anoxic conditions and produce Fe^{2+} ions (Bonneville et al. 2004). Thus, the existence of the zone of elevated Fe^{2+} ions content may be the evidence of a microbiological transformation of iron

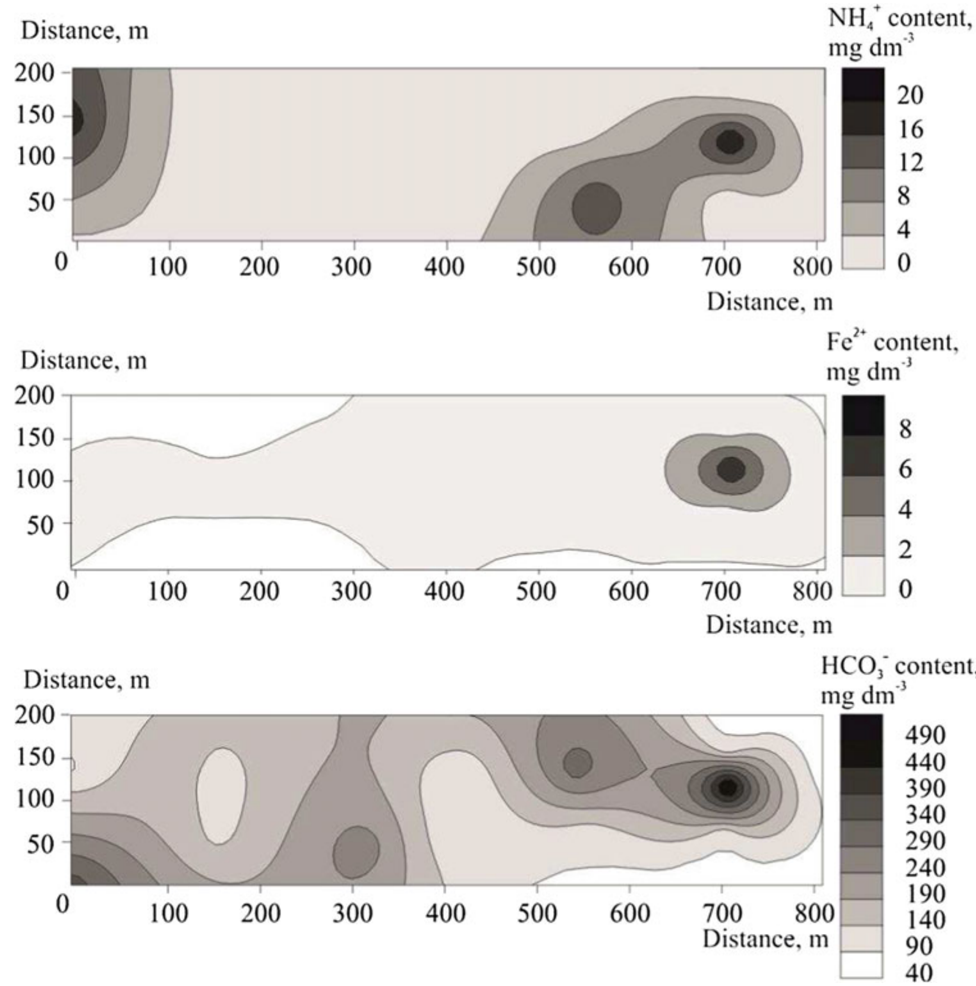

Fig. 1 The distribution of NH_4^+, Fe^{2+}, and HCO_3^- ions in the dam's groundwater, mg dm^{-3}

minerals and rocks of the dam's material that results in the reduction of Fe^{3+} ions to Fe^{2+} ions which actively migrate in water solution and precipitate in the form of trivalent iron hydroxide when gleyed water emerges onto the surface. This explains the considerable increase in the turbidity of water seeping through the dam's body as compared to water from the upstream reservoir.

Water of reservoir seeping through the dam's body was characterized by an elevated content of water-dissolved organic substances (C_{org})—the C_{org} content was 108–122 mg dm^{-3}, while the average C_{org} content in surface water usually did not exceed 30–40 mg dm^{-3}. Mass-spectrometer studies showed that the organic substance dissolved in water is of primarily anthropogenic origin. In our opinion, one of the potential sources of the organic substance entering the reservoir and the dam's body is wastewater discharge from an upstream pulp-and-paper plant.

The analysis of subsurface gases of the dam revealed the occurrence of regions with elevated contents of CH_4, C_2–C_5 hydrocarbons and volatile organic compounds (see Fig. 2).

The studies of the mineralogical composition of the sediment settled at the bottom of dam's drain system revealed a predominance of authigenic minerals (calcite, amorphous iron hydroxides, goethite, hydrogoethite, and pyrite) over allotigenic one (quartz minerals). The newly-formed minerals—intergrowths of calcite and pyrite—were detected (see Fig. 3).

Microbiological investigations of the dam's soil and water revealed the presence of an active metabolizing microbiota in them. Bacteria, isolated from the core and water samples, consumed organic substances, produced gases and leached Fe ions from the dam's material. We detected microorganisms capable to NO_3^--reduction, Fe^{3+}-reduction, SO_4^{2-}-reduction, and methanogenesis in dam's soil and water samples and isolated the enrichment cultures of these microorganisms.

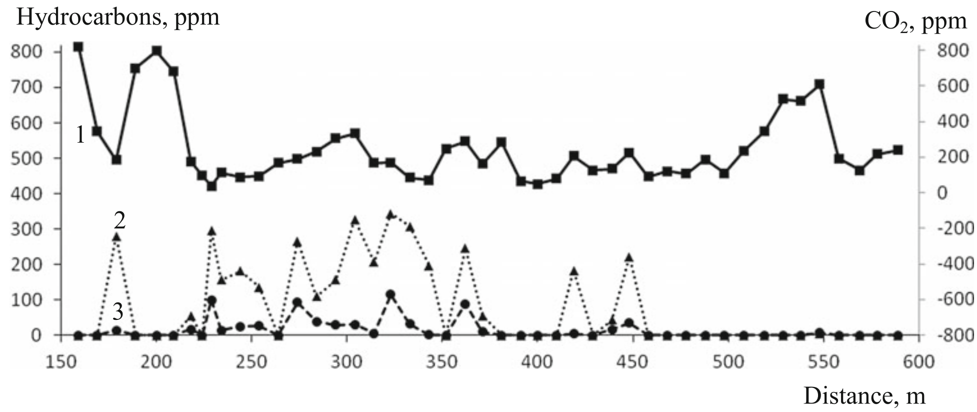

Fig. 2 The content of gases in subsurface air of the dam, ppm (1—CO_2, 2—CH_4, 3—C_2–C_5 hydrocarbons)

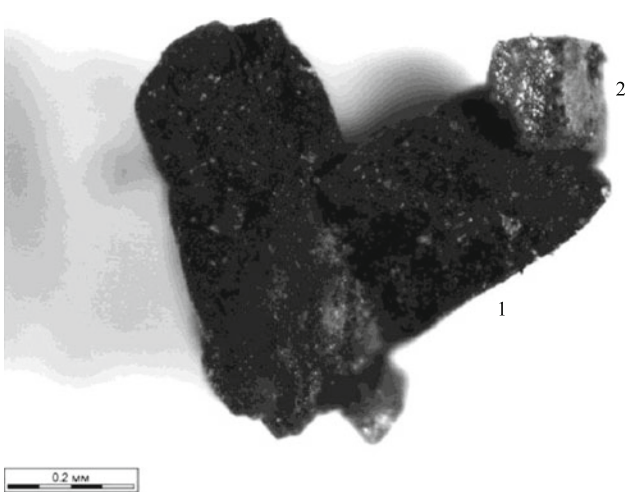

Fig. 3 The intergrowth of calcite (1) and pyrite (2) from the dam's drain system sediment

5 Potential Microbial Activity Suppression Strategies for the Earth Dam

The results of the investigation demonstrate the presence of an active microbiota in dam's soil and water. So, the intensification of bacterial processes, which could be caused by the supply of additional amounts of organic matter, could lead to hazardous changes in physical-mechanical properties of dam's material and, eventually, the unstable state of the dam itself. One of the hazardous changes in the properties of dam's material is the change of bearing strength of the soil as result of gas-forming activity of soil microbiota. Because the content of NO_3^- ions in water samples from the water reservoir and the dam's ground, along with soil samples from the dam's core were negligible, we hypothesized that methanogenesis was the main gas-forming microbial process within the dam. This hypothesis was confirmed with the analysis of subsurface air.

It is known that microbial metabolism of organic matter with Fe^{3+} ions as the electron acceptor is theoretically possible and is more thermodynamically favorable than microbial mineralization of organic matter with sulfate reduction or methane production as the terminal step (Froelich et al. 1979). Moreover, bacteria reducing Fe^{3+} ions successfully outcompete methanogenic bacteria for organic matter (Lovley and Klug 1982), thereby suppressing rates of methane production in environments where Fe^{3+}-containing components are abundant (Lovley and Phillips 1987).

This knowledge allows us to develop the technique to suppress the process of bacterial methane production within the dam's body by amending the soil with a Fe^{3+}-containing substance, $FeCl_3$. Preliminary laboratory experiments using various concentration of aqueous $FeCl_3$ indicated that a minimal 2.5 mg dm^{-3} concentration of aqueous $FeCl_3$ was required to completely inhibit methane production. The efficiency of this $FeCl_3$ concentration was approved in experiment with the dam's material. The technique to suppress gas-forming microbial processes (methanogenesis, in general) was proposed to the dam's officials.

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