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Microbial Changes of the Earth Dam Mechanical Properties and the Improvement of Them

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Abstract

Earth dams are subject to raised liability because changes of their planned engineering and geological indices could lead to weakening or failure of the dam. Microbial processes are a significant but insufficiently studied factor affecting rock/soil properties. When large quantities of water-dissolved organic substances enter an earth dam, the increased activity of soil's microorganisms is able to cause a number of negative effects. We studied one of the largest earth dams in Perm region (Russian Federation) using a complex of field survey techniques. Some signatures of suffosion process were observed during field examination of the dam. Extensive laboratory investigations were carried out and the reasons of observed phenomena were determined. The study of microbial processes influence on dam's soil showed that its deformation modulus changed by a factor of two and more in some circumstances. Such changes of soil properties should be taken into account at planning stage of dam construction. Up-to-date microbiological techniques allow to improve properties of soils during exploitation of the dam. The laboratory experiment on biocementation (i.e. microbially induced calcite precipitation) of dam's soil showed 80% increasing of deformation modulus compared to natural untreated soil. This paper describes the results of laboratory investigations of dam's soil properties. The results of biocementation experiment are also discussed.

Keywords

Soils • Microbiological influence • Mechanical properties • Biotechnology • Dam's stability

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1 Introduction

Microbiological processes are a substantial but insufficiently studied factor affecting rock/soil properties. Microbiota activity influences solid, liquid and gaseous phases of soil, causing changes in acid-alkali and oxidative-reductive environment conditions and, consequently, physical and chemical soil properties (Bolotina and Sergeev 1987; Dashko et al. 2014; Demenev and Khmurchik 2014; Maksimovich et al. 2014, 2016; Radina 1973). When large quantities of organic substances enter the dam's body, rapid growth of microbiota could result in a number of negative processes and phenomena. Nevertheless, biotechnological methods of strengthening soils allow to improve their mechanical properties (DeJong et al. 2006; Weaver et al. 2011).

The purpose of this paper is to assess changes in mechanical properties of dispersive soils in the body and the basement of the earth dam caused by activation of microbiological processes, and to study the patterns of increasing deformation properties in sandy soils when biotechnological methods are used for their improvement.

2 Soils and Ground Water in the Study Area

The studied earth dam is constitutive part of one of the hydroelectric power stations of the Volga-Kama cascade and is located within an urban agglomeration in the Perm region. The dam was built by hydraulic inwash method and is composed of fine sands and gravelly sandy soils. The dam's basement is alluvial deposits represented by clays and heavy loams, fine sands and gravel-and-pebble formations. Clays and loams contain plant remains. The dam's basement also consists of lacustrine-boggy (bayou) sediments represented by clays and loams in high-plastic and fluid-plastic state, sludge deposits of the buried lake and bog muck. The thickness of alluvial deposits is about 14–17 m. Alluvial deposits (Q) cover the middle Permian (P_2) and lower

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Permian (P_1) rocks represented by interstratification of argillite, sandstone and limestone beds of varying thickness (see Fig. 1) (Mamenko 1967).

Waters in the dam's body have close hydraulic connection to alluvial horizon waters, which results in their similar hydrogeochemical content. Generally the dam body waters and alluvial swaters are calcium bicarbonate type, with up to 1 g/dm^3 mineralization. In the areas where sulfates enter the alluvial water-bearing strata from underlying rock mass, anaerobic conditions induce the microbiological process of sulfate reduction identified by representative symptoms.

3 Methods

Examination of microbiological processes occurring in the earth dam from the engineering geology perspective would require the development of an integrated approach. Microbiological processes effect on geological environment is well-studied. But the universal approach to assessment of micribiota activity effect on engineering geology indices is not developed. This paper focuses on the study of mechanical properties of soils and biotechnological method of their improvement; however, the entire bulk of the research includes an array of methods. Standard chemical analysis of 147 samples of water from the drainage system and from the observation wells in the dam was done by using 'Kapel'-104-T' capillary electrophoresis system (Russia) and UNICO spectrophotometer (USA). The gas-analyzer Drager X-am 7000 gas analyzer (Germany), Hanna (Germany) and Solinst (Canada) were used in soil gases survey. Mineralogical analysis of soils was performed on the X-ray diffraction analyzer "D2 Phaser" (Brucker, USA). Physical-mechanical properties of the dam's soil were studied by using laboratory equipment measuring physical and mechanical soil properties. Laboratory microbiological studies of dam's water and soil were done also. Data were processed using special-purpose software: Surfer 8 (Golden Software), RockWorks 14, AutoCAD, Corel Draw etc.

Three wells deep were mechanically drilled in the dam up to 20 m: one well in the bed part and two wells in the plain part of the dam (see Fig. 2). Soils with undisturbed (monolith) and disturbed structure were sampled every meter in depth interval from 2 to 20 m to study their physical and strength properties A total of 45 soil samples was sampled and studied.

Up-to-date geomechanical conditions of the dam's body were studied. The simulation experiments were conducted to assess possible changes in physical and mechanical properties of loamy soils caused by activation of microbiological processes in the researched dam's body.

The first simulation experiment examined the effect of microbiological processes on mechanical properties of soils using enrichment cultures of aerobic heterotrophic and anaerobic sulfate reducing bacteria isolated from sampled soils. Soil samples were exposed to germ cultures up to 64 days during varying incubation periods.

This paper discusses the possibility to stabilize sands of the earth dam body using biocementation technology.

The second experimental set suggested exposure of the researched soils to additional urobacterial biomass to promote calcite sedimentation process. One of the sand biocementation method developments is application of a technology that uses native environment of soils sands introduction of external biomass (Gomez et al. 2014). The ability to decompose urea is generally inherent to

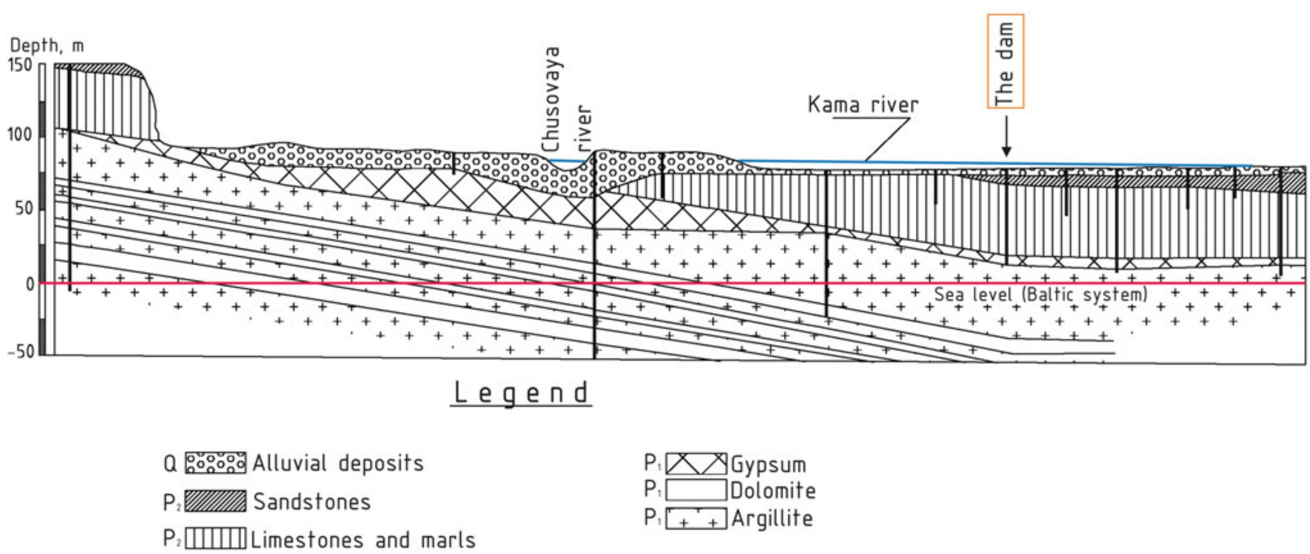

Fig. 1 Geological cross-section of the study area

Fig. 2 Location of wells in the dam

microorganisms; therefore experiments were conducted for improvement of sandy soils by way of calcite sedimentation due to the effect of native microbial flora, i.e. without introduction of additional biomass. Experimental soil samples were exposed to the solution in concentration of 60 ml per 1 kg of soil. The solution was prepared from distilled and river water and enriched with various concentrations of glucose, urea, calcium chloride ($CaCl_2$), and solid beef-peptone extract as organic nutrient. In the first experimental set, additional biomass of urobacteria was also introduced. After 21 days of curing, soil deformation properties were determined by compression tests. In the course of the experiment, gas content was controlled in the artificial environment to determine intensity of microbiological processes. Upon completion of soils exposure, carbonate cementation and strength links formation was captured via microscopy.

4 Results of Investigation

Active microbiological processes in the dam body are confirmed by nitrides concentration content in ground water. Their foci are scattered in the dam body, often in proximity to the lake buried during the dam construction, since the lake's bed deposits contained a lot of readily available organic matter for microorganisms. Based on the result of hydrochemical research, it was established that reservoir basin waters contain less total iron than waters in the dam's body. Besides, signature deposits of hydrous ferric oxides were found at the drain bottom. In this case, iron can come from soils composing the dam base and body, containing iron in various forms. Active iron migration may occur in reducing conditions induced by microorganisms consuming oxygen in the course of their life-sustaining activity. It is notable that migration of mixed valence elements from soil may change their physical and mechanical properties, which, in its turn, impacts operational safety of the earth dam.

It has been established that bacterial exposure of soil samples, both to aerobic and anaerobic microorganisms, reduced soil modulus of deformation examined by compression tests (see Table 1).

For some soils two-fold reduction of the modulus of deformation has been observed as early as on the 29th day of the experiment (light clay—modulus of deformation changed from 3.41 to 1.56 MPa), while for other soils the modulus of deformation (E) decreased only by 1.1 times even after 64 days of the experiment (light loam—modulus of deformation changed from 3.92 to 3.41 MPa). The instance of light silty clay demonstrates that exposure to anaerobic sulfate reducing microorganisms produced more effect on the soil modulus of deformation than exposure to aerobic heterotrophic microorganisms (as of the 29th day of anaerobic microbial exposure, the modulus of deformation decreased almost twice from 2.82 to 1.39 MPa, while the same level of the soil modulus of deformation change in the course of aerobic exposure was achieved only on the 64th day). After bacterial exposure, density of the soils has decreased, including dry unit weight.

Table 1 Results of experiment to reduce of modulus of deformation

Well	Soil	Sampling depth (m)	Enrichment culture of microorganisms	Modulus of deformation (MPa)		
				Initial of test	After 29th day	After 64th day
1	Light silty clay	11.5	Anaerobic sulfate reducing bacteria	2.82	1.39	–
2	Light clay	6.2	Aerobic heterotrophic bacteria	3.41	1.56	–
3	Light sandy loam	6.5	Anaerobic sulfate reducing bacteria	3.92	–	3.41
3	Light silty clay	10.9	Aerobic heterotrophic bacteria	2.82	–	1.39

Table 2 Results of experiment for improvement of sands using various concentrations of substances in solution

№	Base of solution	Concentration of substances (g/l)				Modulus of deformation (MPa)
		Glucose	$CaCl_2$	Urea	Organic nutrient	
1	Distilled water	5	37.5	20	0.75	5.11
2	Distilled water	10	37.5	20	1.5	6.20
3	Distilled water	15	37.5	20	2.25	8.54
4	River water	10	37.5	20	1.5	9.49
5	Distilled water	20	37.5	20	3.0	8.68
6	Distilled water	20	75	40	3.0	8.03

Our results of the conducted experiments for improvement of soils using a biotechnological method showed that soils with introduced additional biomass had 35–80% higher modulus of deformation than abiotic controls.

Modulus of deformation value of sands improved without additional biomass is somewhat less but also effective as a method. Modulus of deformation (E) change has been compared via exposure to substances of varying concentration multiplicity. Substances from 1- to 4-fold concentration were introduced (see Table 2).

The amount of introduced components directly influenced the deformation modulus (E) increase in sands (modulus of deformation changed in several stages from 5.11 to 8.68 MPa with distilled water as solution base and 9.49 MPa when river water was used).

However, the samples with 4-fold concentration of substances in the solution manifested low increase of modulus of deformation versus 3-fold concentration (8.68 and 8.54 MPa respectively). This might be related to approximation to the maximum urea decomposition rate by microorganisms; hence further increase of urea concentration has no effect on increase of the modulus of deformation.

5 Conclusions

Our study reveals the tendency of soil mechanical properties to change due to microbiological exposure. It confirms the need to account for the possible changes in soils physical and chemical properties when ensuring safe operation of the dam or any other buildings and constructions, if their foundation suffers severe microbiological exposure. Meanwhile, not all microbiological processes produce negative effect on soil properties. The basics of microbiological process management, namely the activation of a certain group of native microbial population, allows to redirect the effect of microbiological processes and improve soils deformation properties due to carbonaceous biocementation. Two sets of experiments were conducted: with introduction of nutrient solutions and additional biomass into the researched soils, and with introduction of nutrient solutions sans additional biomass, i.e. by stimulating only the native microbial flora of the soils. Improved soils with additional biomass had 35–80% higher modulus of deformation versus abiotic controls. Modulus of deformation for sands improved without additional biomass is somewhat less but also effective as a method.

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