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Research Article

GAS COMPONENT IN THE UNDERGROUND SPACE: GEOECOLOGICAL ASPECT IN SOLVING ENGINEERING GEOLOGY PROBLEMS

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ABSTRACT

The paper considers the influence of the biochemical gas generation processes on the formation of specific engineering geological and geoecological conditions in the underground space of megacities. It is established that the action of slightly soluble gases (methane, hydrogen, nitrogen) promotes the transition of sandy-clayey soils into a quicksand or thixotropic state. It is noted that when accumulating the slightly soluble biochemical gases, a significant gasdynamic pressure is formed, which causes the transformation of the stress-strain state of soil massif and effects on the deformations of underground structures. It has been found that the presence of highly soluble gases (carbon dioxide, hydrogen sulfide, ammonia) contributes to an increase in the aggressiveness of groundwater against the construction materials of underground structures.

INTRODUCTION

Enhance the safety of urban underground space development and use should be based on its consideration as a multicomponent system consisting of rock (sandy and clayey soils), underground water of different chemical composition and hydrodynamic regime (confined, unconfined and perched aquifers), subsurface microbiota, gases of various genesis and underground structures. The integrity and stability of the structures in such complicated conditions must be ensured not only for construction period but for the entire operational cycle as well as for the reconstruction phase, if necessary.

LITERATURE REVIEW

The theory and practice of engineering-geological and geo-ecological research shows that the study of a gas component (as a part of the subsurface) and its effect on the building structure stability is practically not considered. The latter approval is confirmed by the analysis of existing regulatory documents adopted in the Russian Federation (Table 1).

Based on the experience gained from studying the gas component in the underground space of St. Petersburg and the Yakovlevsky rich iron ore deposit, it has been found that, when evaluating the gas constituent, the following must be taken into account: a gas source, solubility of gas in water (with account of the pressure and temperature), chemical composition, content in the fractured-porous, porous or fractured medium depending on the type of the surrounding soil massif, as well as the possibility of gas accumulation or dissipation.

According to the investigations of the sedimentary strata, the greater part of the gas phase owes its origin to the organic matter, which accumulates mainly in a dispersed form in fine-graded soils containing rich natural biocoenosis and specific groups of microorganisms (Vassoyevich, 1973; Soil science, 1946). At the same time, in the subsurface, it can be frequently found the deep-earth gases, the formation of which is associated with radiation-chemical processes, when under the influence of energy arising from the decay of radioactive elements the radiolysis of organic matter takes place (Natural gases of sedimentary strata, 1976).

RESULTS AND DISCUSSION

The main gases of the sedimentary strata are methane

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Table 1. A comprehensive comparative evaluation of conditions under consideration for the design and construction of above-ground buildings and underground structures in St. Petersburg.

Basic principles of studying the engineering-geological conditions	Regulatory document	According to the regulatory document	According to studies performed in St. Petersburg Mining University
Gases of different genesis	Code of Practice SP 11-102-97: Engineering Environmental Site Investigations for Construction	Gas component has to be studied at sites of filled soils containing inclusions of construction and household waste. The thickness of filled soils must not be more that 2-2.5 m. The gases CH_4 and CO_2 at a content of more than 0.1% and 0.5%, respectively, should be considered as hazardous. When constructing on fill ground, there is a danger of biogas accumulation in basement and underground utilities system of buildings to fire and explosive concentrations of methane (CH_4), which are from 5 to 15% at a content of O_2 – 12,1%	The analysis of gases should be carried out within the zones of interaction between soils and building structures with the division of gases into slightly soluble (CH_4, N_2, H_2) and very soluble (CO_2, H_2S, NH_3). Influence of radon on activation of processes of microbial metabolism and radiolysis of water, soils and building materials have to be taken into account

(CH_4), nitrogen (N_2), hydrogen (H_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), ammonia (NH_3), oxygen (O_2), argon (Ar), krypton (Kr), carbon monoxide (CO) (Trofimov, *et al*., 2005; Dashko, *et al*., 2014). In the upper part of geological cross-section, there are mainly gases of biochemical origin represented by light isotopes of methane (CH_4), nitrogen (N_2), hydrogen (H_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S).

The formation of methane in the subsurface occurs strictly under anaerobic conditions mainly through microbial activity. Organic compounds undergo the methane fermentation as a result of which they can be converted to acetic acid, fermentable according to the chemical reaction $ÑÍ_3ÑÎÎÍ \rightarrow ÑÍ_4+ÑÎ_2$. Methane can be produced due to the reduction of carbon dioxide by molecular hydrogen: $8[H^+] + SO_4^{2-} \rightarrow H_2S + 3H_2O + 2OH^-$. The formation of hydrogen sulphide is associated with the activity of sulfate-reducing bacteria: $8[H^+] + SO_4^{2-} \rightarrow H_2S + 3H_2O + 2OH^-$. The generation of molecular nitrogen is observed during the reduction of nitrates due to denitrifying bacteria activity: $10Í^+ + 2Í^+;\ 2NO_3^- \rightarrow N_2 + 6H_2O$.

To ensure the completeness of geoecological assessment, the solubility of gases is of great importance. According to the solubility (in water), gases are divided into several varieties: very soluble (ammonia); highly soluble (hydrogen sulfide); medium-soluble (carbon dioxide); slightly soluble (methane and its homologues as well as nitrogen and hydrogen) (Fig. 1). It should be noted that the effect of temperature on the solubility of gases is more apparent in the upper part of the underground space, since its increase is related to the heating effect caused by land-based buildings and structures. In this case, the temperature of groundwater rises to 50-60°C. The solubility of gases affects the specificity engineering geological and geoecological conditions. The accumulation of slightly soluble gases changes the stress-strain state of soil massif. The producing of soluble gases increases the aggressiveness of groundwater.

The gas effects can be considered on the example of the underground space of St. Petersburg. The composition of gases, found in the upper part of the underground space, was studied at the beginning of the Twentieth Century (Yakovlev, 1944) in connection with the possibility of using natural methane for illumination of the city. Later, the gas saturation of Quaternary deposits had a decisive influence on the depth of St. Petersburg Metro (Table 2).

The gas showing in Quaternary deposits is associated with a high organic content in biogenic (peat) and marine ("litorinian") deposits as well as the occurrence of gas-producing clayey layers (called "Mikulino layers") containing bituminous organic matter. In addition, there have been cases of molecular nitrogen release from the Lower Cambrian and Upper Vendian bedrocks in the north of the city that were not related to biochemical processes.

In recent years, the intensity of gas generation in the subsurface of the city has increased significantly. A number of gas releases, accompanied by both emissions of gas-saturated running soils and gas inflammations, has been observed. However, the actual number of gassing sites is much larger, since only episodes with an emergency character are usually recorded. They were repeatedly noted in the

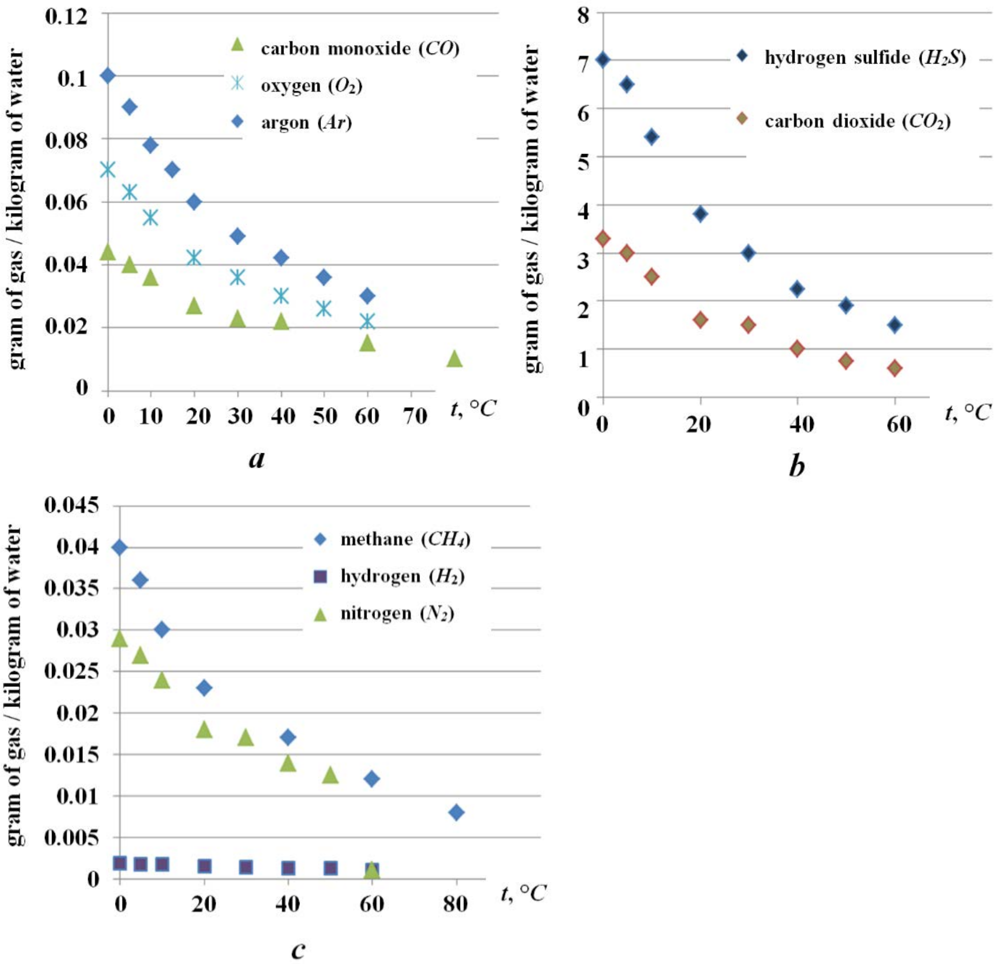

Fig. 1 Solubility curves for different gases (a, b, c) as a function of the environment temperature.

Table 2. Composition of natural gases found in the underground space of St. Petersburg and adjacent area (in Quaternary and pre-Quaternary deposits) (Dashko, *et al.*, 2014).

Place of sampling	H_2S	CO_2	O_2	CH_4	H_2	N_2, rare gases	Ar, Cr, Xe	He, Ne
"Utkina zavod"	-	0.3	1.3	53.1	-	45.3	0.483	0.021
"Krivoe koleno", Zinov'evo pier	-	1.1	1.5	56.1	-	41.3	0.512	0.023
Village Bol. Porogi, near the Roslova stream	-	0.5	0.2	72.6	-	26.7	0.305	0.06
Station "Sortirovochnaya"	-	4.1	-	93.2	-	2.7	0.048	0.005
Nevdubstroj	-	1.3	0.2	91.4	-	7.1	0.115	0.0014
Aptekarskij Island, Grota street*	-	-	1.8	-	-	98.2	1.082	N/A
Bezymyannyj Island, Rizhskij Ave., Brewery them. Stepan Razin*	-	-	0	-	-	98.0	1.013	N/A
*- The Upper Vendian sandstones								

Central, Frunzensky, Nevsky, and Krasnogvardeysky districts as well as in Kupchino and other sites. The gas composition is dominated by methane and carbon dioxide. The nitrogen content, as a rule, does not exceed 2-3%. The isotopic composition analyzes of gases have shown that they had a predominantly biochemical origin (Dashko, *et al.*, 2014). Active generation of gases is associated with the intensive contamination of the underground environment owing to various sources (Fig. 2).

Accordingly, the numerous studies, conducted by the Department of Hydrogeology and Engineering Geology of St. Petersburg Mining University, have shown that the analysis of the gas component effect on engineering-geological conditions should be based on the following positions: 1) an assessment of the strength loss of sandy-clayey soils due to the accumulation of "solid" bubbles of slightly soluble gases (methane, nitrogen, hydrogen; 2) a possibility of transformation of the soil massif stress-strain state

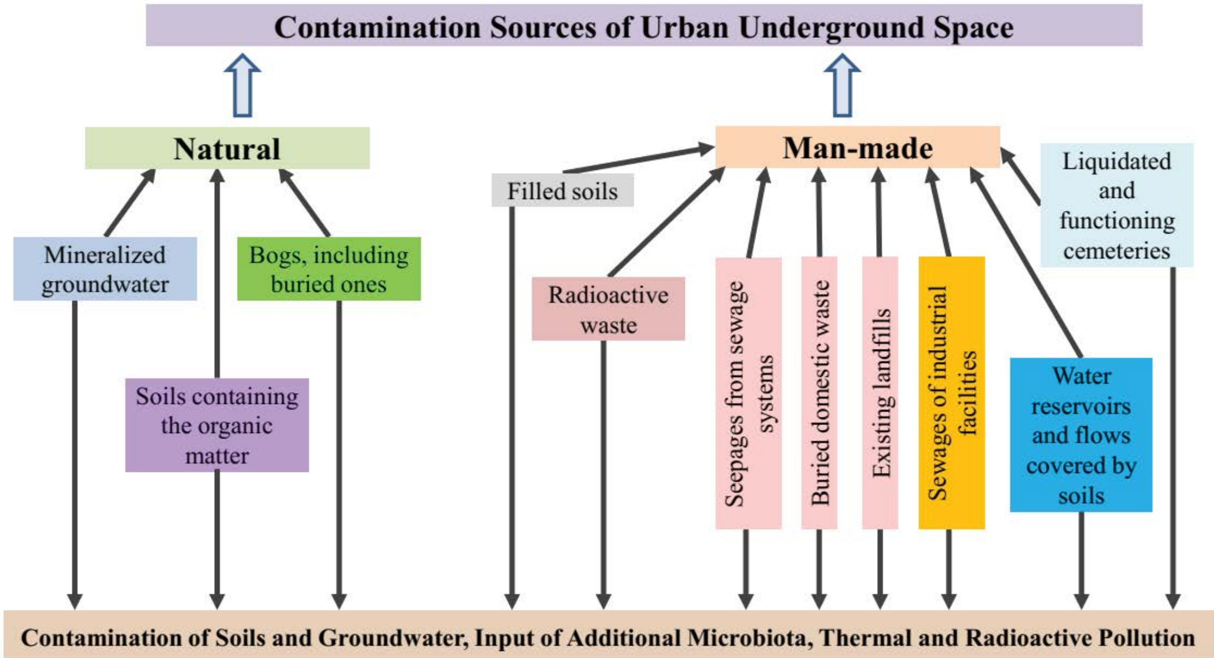

Fig. 2 Scheme of natural and man-made factors affecting on the microbial activity in the underground space of megacities (Dashko, 2007).

due to the gas-dynamic pressure increase caused by the accumulation of the above-mentioned slightly-soluble gases in the pore space of soils when their dissipation is impossible; 3) a presence of water soluble gases (carbon dioxide, hydrogen sulphide) which are capable of increasing the groundwater aggressiveness against the materials of underground structures. These points have to be considered in more detail.

1. In conditions of even a small accumulation of slightly soluble gases (CH_4, N_2, H_2) in sandy-clay soils, the increase of their gas saturation causes a change in the stress-strain state. The gas bubbles with a minimum radius, trapped in the pores of dispersed soils, do not contract. According to research, carried out by physicists in the field of gas dynamics, such bubbles refer to "solid bubbles" with a high value of surface tension and high internal pressure. They are capable of destroying the structure of pore water. In this case, the thixotropy of clay soils significantly increases that is observed even under small dynamic and vibrational influences (caused by work of above-ground and underground transport, pile driving, construction of enclosing structures, etc.). It has been experimentally established that the generation of slightly soluble gases in sandy soils leads to the appearance of the effect of "ball bearings" and the removal of friction, which facilitates the transfer of sands to the state of heavy liquid (quicksands), regardless of their grain size distribution. This is especially typical for cases when there is no dissipation of gases from sands.

2. The gas component has effect on the stress-strain state of the soil massif that governs its stability as well as the nature and intensity of the filtration consolidation process, which depends on the pore size of clay soils. Famously, the pore size in clays varies within wide limits: from hundredths to several micrometers. As noted earlier, when compressing the gas saturated soils, it can pass from the liquid phase or the occluded state to the free state, thereby promoting the development of long and continuous settlements of building structures. As is known from the theory of filtration consolidation, even a slight gas saturation leads to a reduce in pore pressure and slowdown in the consolidation process. With a decrease in the water saturation coefficient to 0.95 or less, the process of clay soil compaction due to outflow of water is practically not realized.

Furthermore, the change in the stress-strain state of the gas-saturated soils, surrounding the underground structures, leads to the development of their uneven deformations and the formation of fractures in their constructions that can be studied on the example of one of the routes of St. Petersburg Metro, located in the southeast part of the city (Fig. 3). Variation of the gas-dynamic pressure along the tunnel creates sharply differentiated conditions for the development of their displacements of different amplitudes. The uplifting of tunnels is observed on the local sections of the route where the most favorable conditions for the accumulation of gases (in isolated sand lenses), coming from the Mikulino gas-generating layers, has formed. It should be noted that the Mikulin bituminous soils are characterized by a high microbial activity, what is causing their biocorrosive aggressiveness against the tunnel materials, including cast iron and reinforced concrete.

3. Intensive biochemical generation of water-soluble gases (carbon dioxide and hydrogen sulfide) along with the accumulation of such metabolic products of bacteria as mineral and organic acids (HNO_2, HNO_3, H_2SO_4, CH_3COOH, etc.) contributes to an increase in the groundwater aggressiveness against the foundation materials and tunnel linings (Fig. 4). Among the slightly soluble gases, hydrogen is of the greatest importance. The presence of hydrogen in groundwater increases the brittleness of steel that in turn predetermines the active development of corrosion processes of underground pipelines.

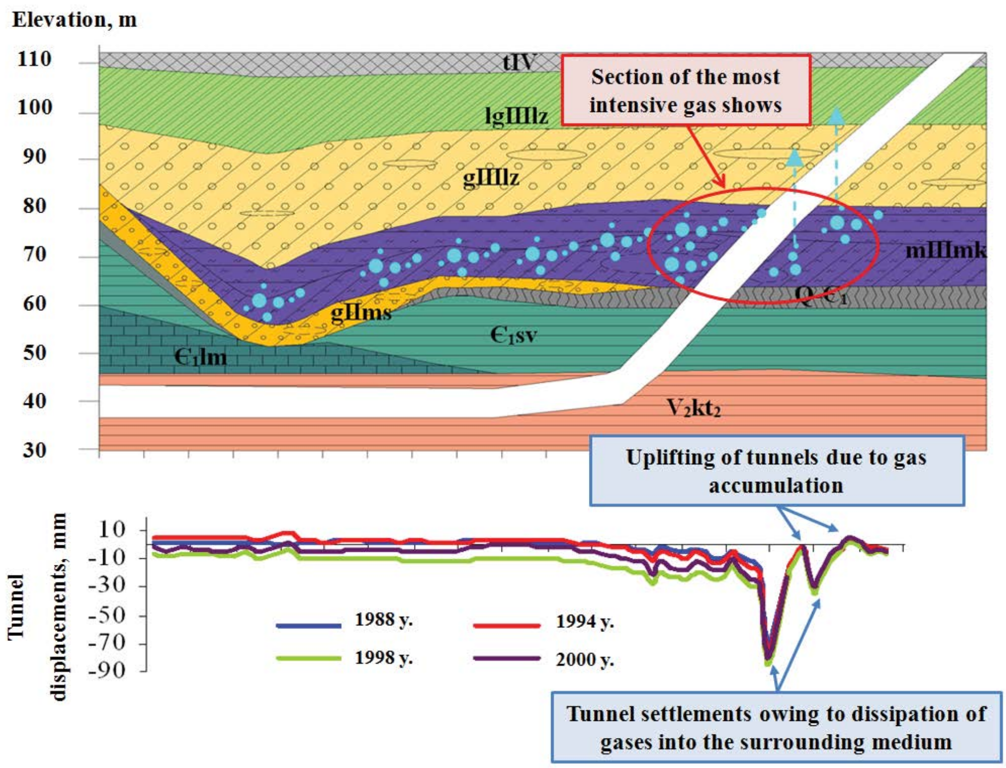

Fig. 3 Alternating vertical displacements of tunnels in relation to the gas-dynamic pressure variations along the route.

Fig. 4 Growth and leaching with a rusty wet coating (a); Stalactite on the lining stiffener rig (b).

CONCLUSION

Even an insignificant intensity of biochemical gas formation can lead to a deterioration of engineering-geological and geoecological conditions, a decrease in the bearing capacity of soils, and, accordingly, the transition of building structures to a pre-emergency or emergency state that should be taken into account when designing structures of various purposes. The presence of water-soluble gases (carbon dioxide, hydrogen sulphide, ammonia) contribute to increasing the aggressiveness of groundwater, the development of corrosion and biocorrosion against constructional materials that involves the use of special inhibitors (biocides), as well as microbial-resistant materials for restoration and construction works, especially within the zones which are potentially dangerous with regard to a biochemical gas generation.

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