Groundwater modification and its effect on the infrastructure of Yakutsk

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Abstract: The rapid changes in geological conditions, intensive soil salinization, water table rise and increased salinity of suprapermafrost water, and extensive development of cryopegs in the Yakutsk area are discussed. The progressive development of cryogenic processes leads to changes in the bearing capacity of soils and to damages of buildings and structures.

Keywords: city, permafrost, suprapermafrost water, cryogenesis, geochemistry

Introduction

Yakutsk is one of the largest and oldest cities in northeast Russia. The city is located on the left bank of the Lena River in its middle reach. The Lena valley within city limits is a flat terraced lowland dissected by the Lena and its tributaries, oxbows and lakes. Chernozem-meadow and meadow-chernozem soils are developed on the river terraces. Sod-meadow alluvial soils occur on the floodplain, islands and, occasionally, on the first terrace. Soils are predominantly saline.

The Yakutsk region is an ancient trough of the Siberian Platform filled with Mesozoic marine deposits (conglomerates, sandstones), which are overlain by younger materials of Neogene and Quaternary age (sands, loess-like loam). Permafrost thickness at Yakutsk is 200 to 250 m. Ground temperature depends on the date of construction and varies from -2° to -8°C. An open talik is present beneath the main channel of the Lena. The active layer varies in depth from 1.8 to 4.0 m, the dominant range is between 2.5 and 3.0 m.

Results and discussion

Permafrost and related processes exert a profound influence on the city's infrastructure. One of the distinctive features of Yakutsk is that buildings are elevated above the ground surface on piles in order to prevent permafrost soil thawing. In Central Yakutia, where the city is located, water losses by evaporation are much higher than precipitation. Natural conditions are thus not favourable for ponding at the surface. However, the water balance in the urban area is considerably modified by anthropogenic factors. The inflow term of the balance increases substantially due to water leakage from utility lines (water and heat supply lines, sewage lines, etc.). Leakage is the greatest in wintertime when it results in icings. The volume of an anthropogenic icing averages 250-400 m^3, and the total volume for the city is estimated to be 200,000 m^3. Water losses from the lines lead to oversaturation of soils. Because of the flat topography, and the absence of slopes and water divides, a signifi-

Scientific paper

cant portion of the city is covered by swamps and ponds. The high rate of ponding is one of the important geoecological characteristics of the city (Table 1).

Table 1. Change in the ponding area in Yakutsk

Year	Area, km^2	Period	Change in area, %
1971	8.7	1971-1989	24
1989	10.8	1989-1996	35
1996	14.6	1971-1996	68

Road embankments act as a specific frozen curtain and obstruct suprapermafrost water flow along topographic lows from the urban territory to the Lena River. Localization of suprapermafrost water has a cellular pattern. In addition road pavements and concrete covers around or below buildings have significantly reduced water evaporation from the soil. All these factors have caused a substantial decrease of the outflow term of the water balance within the city limits. The magnitude of ponding and inundation has approached a catastrophic level (MAKAROV AND SHATZ, 1998).

Nearly everywhere in the city the active layer contains groundwater with high contents of chlorides, sulphates and bicarbonates. The salts disturb the ice-cementing bonds in the underlying permafrost, thus accelerating permafrost degradation and reducing the bearing capacity of foundation soils. The Yakutsk area is characterized by the high rates of chemical migration, which results in salinization of the permafrost at depth and its change into a plastically frozen or a thawed state. In places, TDS values of the suprapermafrost water are as high as 50-100 g/L.

The presence of a cryogenic aquiclude, in combination with the negative mean annual temperature and the very low winter temperatures, is responsible for extensive cryogenic metamorphization of natural waters. Freezing of water in soil is accompanied by salt crystallization with decreasing temperature (ZUBOV, 1945). The general trend in cryogenic metamorphization in the zones of anthropogenic impact is an increase in TDS and in contents of chlorides, sulphates, ammonium and heavy metals (Mn, Cu, Cr) in natural waters. Repeated freeze-thaw cycles concentrate dissolved contaminants in gravitational water to form a cryopeg. Cryopegs, intrapermafrost saline water bodies, are lens-like in shape and tens of meters in length (Figure 1). A typical example is the lens-like cryopeg in the central part of Yakutsk, which was encountered by drill holes at 7.3 m depth in fine-grained sands and had a water temperature of -3.5°C. The freezing point of the soils is 3-5°C below zero. As a result, the soils have a subzero temperature but remain unfrozen, and thus are unsuitable for the use of passive construction methods.

The results of ecogeochemical monitoring (MAKAROV; 1985, 1998) indicate that Yakutsk is characterized by heavy anthropogenic pressure on the ecosystems. The reasons are the unfavourable climatic and geotechnical conditions on the one hand and the erroneous construction practices on the other. Man-induced geochemical anomalies are observed in all elements of the natural environment (MAKAROV AND VENZKE, 2000).

Soil is one of the depositaries for contaminants. Salinity of the active layer is dominated by sulphates and decreases in order: $SO_4^{2-} > Cl^- > HCO_3^-$. Lithochemical anomalies vary con-

siderably in size, from 100-200 ha (mercury, lead, silver) to 1-10 ha (lithium, vanadium, cobalt, gallium). Four large lithochemical anomalies have been detected at Yakutsk where soil salinity exceeds 1 %/100 g. Soil salinity within the anomalies is dominated by chlorides and sulphates with Cl^- and SO_4^{2-} concentrations >10-20 mg×eq/L. Geochemical monitoring in the Yakutsk area has allowed a qualitative and quantitative appraisal of soil salinization. It has been found that soil alkalinity is increasing most rapidly. The chemical characteristics of the soils – pH, organic matter, NO_3^-, Cl^-, Fe, and Mg, contents of Mg salts and alkali – indicate that they are very aggressive and corrosive for engineered structures.

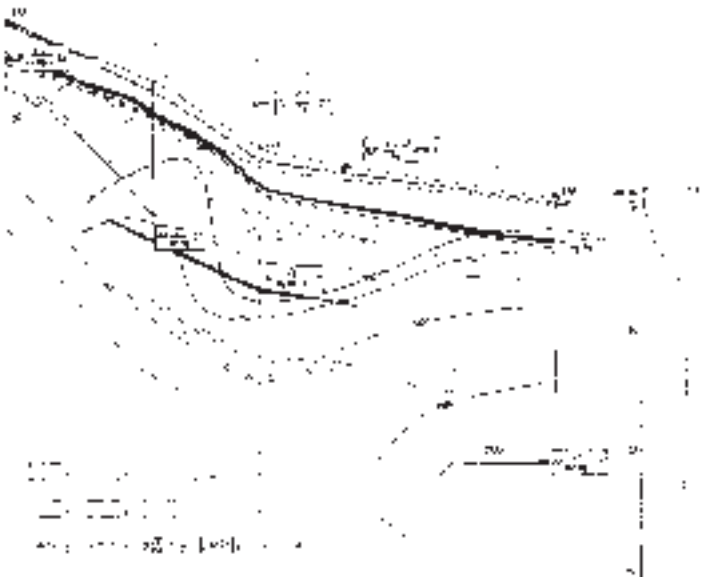

Figure 1.
Chemical composition of groundwater at Yakutsk (District 72).
(1) fill
(2) medium sand
(3) fine sand
(4) sandy loam
(5) loam
(6) ground water
(7) permafrost table
(8) water chemistry: TDS in g/L, dominant ions and pH
(9) distribution of copper in water in mkg/L

Observations on the behaviour of soil solutions provided an understanding of their seasonal patterns. Most significant changes in the fluxes of major and trace constituents, as well as in pH and redox potential that control chemical transport in the upper horizons of the active layer occur before and after the winter when rapid temperature changes and phase transformations of water take place. Prior to the winter, most components forming an anthropogenic anomaly are accumulated near the surface. In winter, penetration of the freezing front causes dissolved contaminants to concentrate and migrate downward, resulting in a decrease in salinity of the upper part of the active layer. Greatest seasonal fluctuations are characteristic of the Cr, Ag, Pb, Mo, S, Ca, Na, Cl, Mg and Sn compounds, whose concentrations in pore water vary three- to thirty-fold.

The productivity of anthropogenic geochemical fields in the upper part of the active layer, i.e. the volumes of dissolved constituents in the upper 1 m of soil in spring and autumn, was estimated (Makarov, 1998). The difference between the spring and the autumn values gives the amount of substances that have been transferred to the deeper horizons of the active layer and into the permafrost during the winter months. The magnitude and intensity of cryogenic redistribution of contaminants can be estimated from the annual balance of the productivity of anthropogenic anomalies. The annual balance of major constituents at Yakutsk

is 13,800 t for SO_4^{2-}; 8,800 t for Cl^-; 7,000 t for Na^+; and 2,400 t for Ca^{2+}. For heavy metals that affect electrochemical dissolution of metal structural elements (Cu, Sn, Pb and Ag), the difference is two to four orders of magnitude smaller.

The depth of contaminant penetration into the permafrost depends on a concentration gradient and geochemical properties of the elements that form an anomaly. Salt concentrations in the upper 0.5 m of soil decreased over the last few years owing to the reduction of atmospheric deposition. The area of saline soils with concentrations >0.2 % decreased more than two-fold: from 71 % in 1984 to 27 % in 1997.

The lack of adequate information on the dynamics of permafrost and geological conditions has resulted in a number of problems in the maintenance and construction of buildings and structures in Yakutsk. Progressive development of cryogenic processes changes the bearing capacity of frozen soils, damages the buildings and deforms the road pavements (POPENKO, 1997). The main causes of maintenance and developmental problems in Yakutsk are alteration of permafrost conditions, soil salinization, rise of water table and increase in TDS of suprapermafrost water, and extensive development of cryopegs. The majority of buildings in danger of failure (about 70 %) are located within the oldest section of the city built by the early 20th century. It is worth noting that only Ľ of the emergency buildings are within the near-surface geochemical anomalies. Obviously, present-day salinization is limited to the upper horizons of the active layer, while cryopeg development is localized.

CONCLUSIONS

Anthropogenic alteration of the chemical composition of suprapermafrost water affects underground utilities, foundations, basements, road pavements and other structures. Multiple changes in acidity/alkalinity and in contents of organic and other constituents make the groundwater more aggressive and increase the corrosiveness of soils.

Natural and man-induced geological processes and phenomena pose an increasing threat to the city's infrastructure and give rise to ecological problems. The main approaches to improving the ecogeochemical situation in Yakutsk are planting of greenery, removal or containment of toxic substances by geochemical barriers, and cleaning of lakes and stream drainages.

REFERENCES

MAKAROV, V. N. (1985): *The Geochemical Atlas of Yakutsk*. Yakutsk: Permafrost Institute, 65 p.

MAKAROV, V. N. (1986): Geochemistry of cryogenic soils in urban areas. In: *Geochemistry of Technogenesis*. Novosibirsk: Nauka, pp.118-124.

MAKAROV, V. N. (1998): *Geochemical Fields in Permafrost*. Yakutsk: Permafrost Institute, 116 p.

MAKAROV, V. N., SHATZ, M. M. (1998): Conprehensive remote sensing andgeochemical monitoring of the ecological situation un the permafrost regions (North-Eastern Asia). *International II Meeting "Permafrost and actions of natural or artificiŕl"*, Orsay, Oktober 21-23, 1998, pp. 149-150.

POPENKO, F. E. (1997): On engineering protection of Yakutsk from flooding and geological hazards. In: *Yakutsk – the Capital of the Northern Republic: Global Problems*. Workshop Proceedings, 16-17 November 1995, Yakutsk, Russia. Part II. Yakutsk: Fond Gradospfera, pp.68-74.

ZUBOV, N. N. (1945): Ice in the Arctic. Moscow: Glavsevmorput, 360 p.