Soil salinization in northern urban areas is an engineering problem

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Abstract: The paper reports 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 area of Yakutsk. The progressive development of cryogenic processes leads to changes in the bearing capacity of soils and to damage of buildings and structures.

Résumé: Rapport se montrer rapide changement conditions géologiques, intense terrain salinite, sous-permafrost eau, et se développer cryopegs a Yakutsk. Développer cryogéne processus amener á dimension solidité terrain et dégât edifices et bâtimentes.

Keywords: geochemistry, permafrost, soils, collapse, urban geosciences

INTRODUCTION

Yakutsk is one of the largest and oldest cities in northeast Russia. Since its foundation by Cossacks in 1632, it has been an administrative, political and trade center of northeast Siberia. 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 River and its tributaries, oxbows and lakes. The width of the Lena River (together with its arms) at Yakutsk is 5 to 7 km. The north-trending valley slopes are 17 to 20 km apart. The left slope, 3-4 km west of Yakutsk, is 80 to 100 m high and passes into a rolling plateau. The slope line is disrupted by deeply-incised valleys of ephemeral streams and creeks. The right slope of the valley is lower (30-40 m relative the valley bottom) and lies 12-14 km east of the city.

Geologically Yakutsk is within 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).

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.

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.

PERMAFROST AND GROUNDWATER CHEMISTRY

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 to prevent permafrost soil thawing.

Nearly everywhere in the city the active layer contains groundwater with high contents of chlorides, sulfates 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 (Table 1).

Table 1. Precipitation of salts with decreasing temperature, after Zubov (1945)

T, °C	Salt
-1.9	$CaCO_3$
-8.2	$Na_2SO_4\ 10H_2O$
-23.0	$NaCl\ 2H_2O$
-36.0	$MgCl_2\ 6H_2O$
-55.0	$CaCl_2\ H_2O$

The general trend in cryogenic metamorphization in the zones of anthropogenic impact is an increase in TDS and in contents of chlorides, sulfates, 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 metres in length.

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 (TDS – g/l; ions - %-eq.):

$$\begin{matrix} \text{Cl } 90\ \text{SO}_4\ 7\ \text{HCO}_3\ 3 \\ \text{TDS } 87.7\ \text{---------- pH } 7.3 \\ \text{Na } 52\ \text{Mg } 41\ \text{Ca } 7 \end{matrix}$$

The freezing point of the soils that contain water with this salinity level 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, conducted by Makarov (1985, 1998), indicated that despite the relatively small size and the low concentration of industry Yakutsk is characterized by heavy anthropogenic pressure on the ecosystems. The reasons are the unfavorable 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, atmosphere, snow cover, natural waters and vegetation.

Soil is one of the repositories for contaminants. The accumulation level of contaminants in the soil depends on their concentration in airborne deposits and effluent discharges, as well as on the volume and duration of inputs. Anthropogenic impacts on the soils at Yakutsk have caused significant changes in their chemical composition. Salinity of the active layer is dominated by sulfates and decreases in order: $SO_4^{2-} > Cl^- > HCO_3^-$. Lithochemical anomalies vary considerably in size, from 100-200 ha (mercury, lead, silver) to 1-10 ha (lithium, vanadium, cobalt, gallium). According to Makarov (1985, 1986) the anomalies spread out from the industrial sites to residential areas.

Four large lithochemical anomalies have been detected at Yakutsk where soil salinity exceeds 1%/100 g: northern and central parts, Zalog, and residential blocks near Saysary Lake (Figure 1).

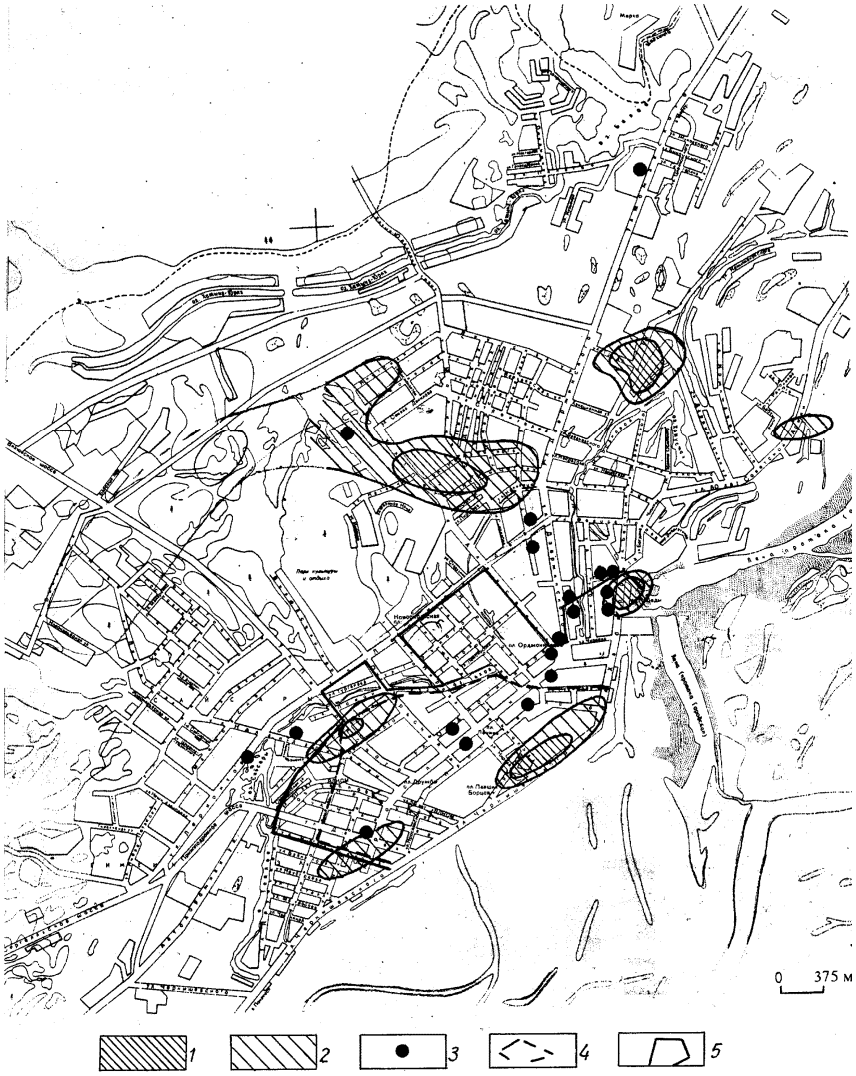

Figure 1. Distribution of saline soils and emergency buildings.
(1) emergency buildings; saline soils (salt sum, %): (2) 0.5-1.0 and (3) >1.0; city limits (4) in 1821 and (5) in 1908.

Soil salinity within the anomalies is dominated by chlorides and sulfates 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, mainly by chlorides and sulfates. 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.

Observations on the behavior 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 for Yakutsk, by 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 judged 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 (Table 2).

Table 2. Average content and productivity of anthropogenic geochemical anomalies in pore water for different seasons

Component	Average content*		Productivity of anomaly, t		
	Autumn	Spring	Autumn	Spring	Difference
SO_4^{2-}	30	5.2	25,500	11,700	13,800
Cl^-	7	2.6	9,800	1,040	8,760
Na^+	20	4.8	8,900	1,900	7,000
Ca^{2+}	12.7	2.5	4,000	1,600	2,400
HCO_3^-	3.3	2.6	3,350	2,900	450
Mg^{2+}	5.5	1.9	1,100	1,000	100
Cu	1.0	0.75	3.0	2.6	0.4
Pb	0.25	0.015	0.3	0.06	0.24
Sn	0.015	0.005	0.1	0.01	0.09
Ag	0.075	0.005	0.03	0.01	0.02

Note: *Major constituents are in mg·eq/L, minor constituents are in mg/kg.

The depth of contaminant penetration into the permafrost depends on a concentration gradient, i.e. contaminant contents in suprapermafrost water, 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 (Table 3).

Table 3. The areal change in saline soils (% of the total area of Yakutsk)

Salt sum, %	1984	1997
<0.1	17	50
0.1-0.2	12	23
0.2-0.5	53	19
0.5-1.0	13	5
>1.0	5	3

The lack of adequate information on the dynamics of permafrost and geological conditions has resulted in a number of severe problems in the maintenance and construction of buildings and structures in Yakutsk. According to Popenko (1997) progressive development of cryogenic processes changes the bearing capacity of frozen soils, damages the buildings and deforms the road pavements. 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. As a result of these processes, most construction sites in the city have saline foundation soils. Highest salinities are observed within the active layer, but the upper permafrost can also have more than 0.25% salinity. Investigations of the adfreeze temperature – salinity relationship indicate that the bearing capacity of soils is significantly reduced even at the salt contents below 0.25%.

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 (see Figure 1). It is worth noting that only a quarter 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 (Figure 2).

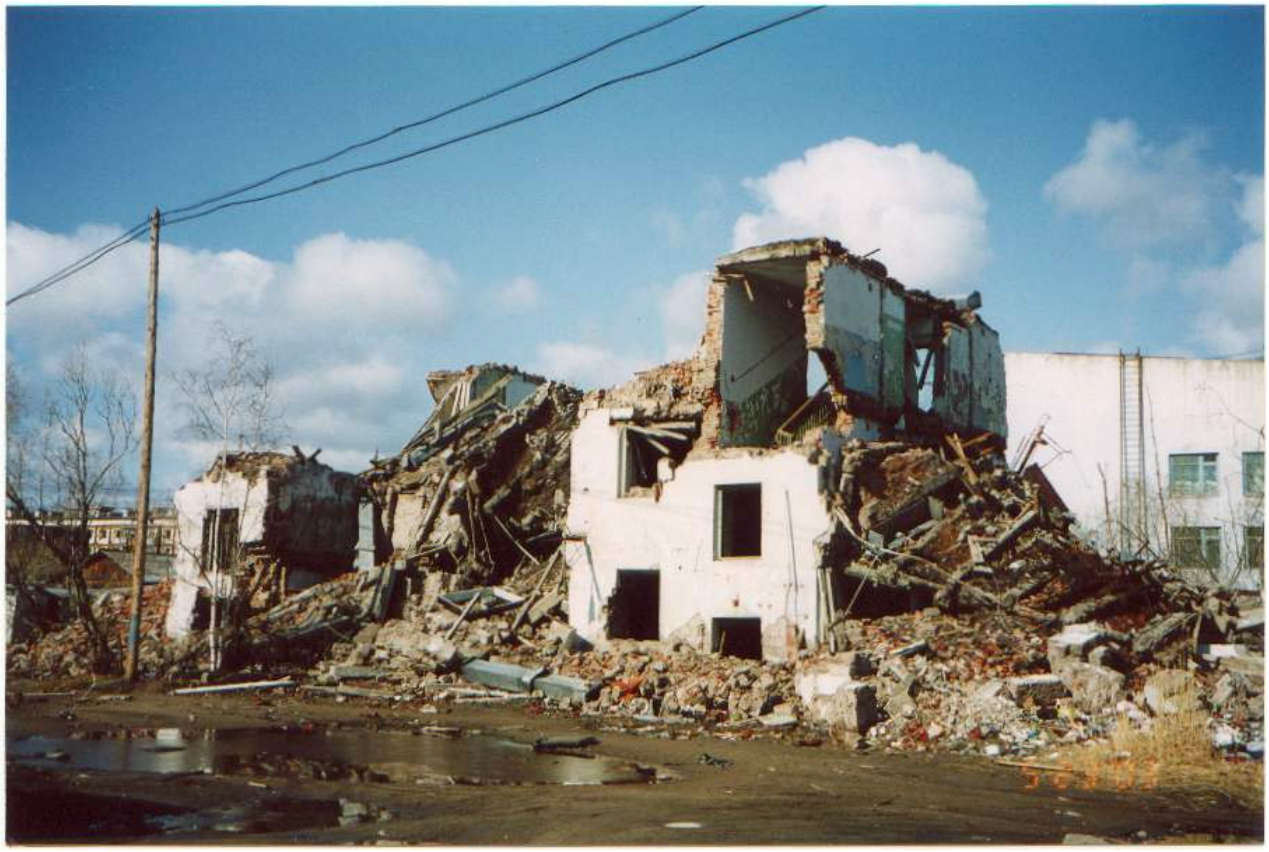

Figure 2. Destruction of buildings in Yakutsk

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.

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