ISSN 2411-3336; e-ISSN 2541-9404

JOURNAL OF MINING INSTITUTE

Zapiski Gornogo instituta

Journal homepage: pmi.spmi.ru

Research article
UDC 624.131.7

The Upper Kotlin clays of the Saint Petersburg region as a foundation and medium for unique facilities: an engineering-geological and geotechnical analysis

Regina E. DASHKO, Georgiy A. LOKHMATIKOV✉
Saint Petersburg Mining University, Saint Petersburg, Russia

How to cite this article: Dashko R.E., Lokhmatikov G.A. The Upper Kotlin clays of the Saint Petersburg region as a foundation and medium for unique facilities: an engineering-geological and geotechnical analysis. Journal of Mining Institute. 2022. Vol. 254, p. 180-190. DOI: 10.31897/PMI.2022.13

Abstract. The article reviews the issues concerned with correctness of the engineering-geological and hydrogeological assessment of the Upper Kotlin clays, which serve as the foundation or host medium for facilities of various applications. It is claimed that the Upper Kotlin clays should be regarded as a fissured-block medium and, consequently, their assessment as an absolutely impermeablestratum should be totally excluded. Presence of a high-pressure Vendian aquifer in the lower part of the geological profile of the Vendian sediments causes inflow of these saline waters through the fissured clay strata, which promotes upheaval of tunnels as well as corrosion of their lining. The nature of the corrosion processes is defined not only by the chemical composition and physical and chemical features of these waters, but also by the biochemical factor, i.e. the availability of a rich microbial community. For the first time ever, the effect of saline water inflow into the Vendian complex on negative transformation of the clay blocks was studied. Experimental results revealed a decrease in the clay shear resistance caused by transformation of the structural bonds and microbial activity with the clay's physical state being unchanged. Typification of the Upper Kotlin clay section has been performed for the region of Saint Petersburg in terms of the complexity of surface and underground building conditions. Fissuring of the bedclays, the possibility of confined groundwater inflow through the fissured strata and the consequent reduction of the block strength as well as the active corrosion of underground load-bearing structures must be taken into account in designing unique and typical surface and underground facilities and have to be incorporated into the normative documents.

Keywords: Upper Kotlin clays; fissured-block medium; Vendian aquifer system; groundwater inflow; tunnel deformation; typification of geological profile; reduction in clay strength; micro-organisms; biocorrosion

Received: 16.12.2021 ***Accepted: 07.04.2022*** ***Online: 31.05.2022*** ***Published: 13.07.2022***

Introduction. Increasing height of surface buildings and facilities, along with the active use of underground space with the development of the metropolitan city, raise the question of correct analysis of the bedclay sediments in the Saint Petersburg region, which are considered as a safe foundation in the normative documents. These formations are used as a medium for construction of underground facilities, first of all those used as transport infrastructure, e.g. tunnels and underground metro stations [1-3], and are also considered as a potential geological formation to isolate extremely hazardous industrial waste, including radioactive waste [4].

Practical experience in construction and operation of underground and surface facilities that interact with the Upper Vendian clays shows that the reliability of the engineering-geological, geotechnical and hydrogeological [5] analysis of these formations requires a non-conventional approach [6-8] to assessing the specific features of their fissuring, and accounting for the structural and tectonic conditions [9, 10], as well as transformation of such sediments under the action of natural and man-made factors [11, 12], associated with the specific characteristics of underground space development and use in the Saint Petersburg region both within and outside of the city infrastructure.

Journal of Mining Institute. 2022. Vol. 254. P. 180-190

Discussion. ***Engineering-geological and hydrogeological assessment of Vendian bedclays.*** Within the discussed area, the Vendian bedclay sediments include formations of the Upper Vasileostrovskaya Series of the Kotlin Regional Stage of the Upper Vendian Period (Upper Kotlin clays). These formations are attributed to the marginal-marine facies, and they are characterized as greenish-grey hydromicaceous kaolinite clays of high lithification with an increased silt content and alternation of thin silty and clayey bands. Until the middle of the 20th century, these sediments were dated as Lower Cambrian and referred to as the Laminarite clays because of the organic remains of the *Laminarites* algae, which are often traced on the stratification planes [13].

Studies of the Upper Vendian bedclays and their fissuring were actively started in the middle of the 20th century by the researchers of Saint Petersburg Mining University [14-16].

The specific features in development of fissuring of the Upper Vendian bedclays are consistent with the geological history of the Saint Petersburg region, which can be divided into four stages (Fig.1).

- The stage of progressive lithogenesis lasted more than 300 Ma until the Late Carboniferous Period, during which the described area experienced a gravitational compaction and dehydration of marine sediments under the pressures of up to 9-10 MPa. At this stage, strong structural bonds as well as subhorizontal lithogenetic fractures were formed [17]. During this active tectonic period in the region, near-vertical or steeply dipping fractures were formed and the clayey formations were divided into blocks (tectonic fracturing).
- Starting from the end of the Carboniferous Period and until the Pleistocene Epoch, the region experienced a long continental period in its development, i.e. the regressive stage of lithogenesis. This period witnessed exposure of clays to the daylight surface, their further hydration, opening of the previously closed fractures and formation of physical weathering fissures. Development of the river valleys in the region started in Late Neogene. The valleys were mainly attributed to tectonic faults, with valley sides angles of 12-16° (rarely up to 18°) within the clayey rock formation. Elastic repulse fractures, subparallel to the valley sides, as well as landslip fractures, were formed at this stage. Currently, these river palaeovalleys are filled with Quaternary sediments and their penetration into the Vendian clayey formations can reach 90 m (Vasilievsky Island, Muzhestva Square).
- The third stage began in the Early Quaternary Period with onset of the continental glaciation. During this period in the course of glacial and interglacial phases, the bedclays experienced significant cyclic loads, reaching 10-30 MPa at different stages. In addition to the tectonic and non-tectonic fractures, three systems of glaciotectonic fractures developed as the glacier was moving, one of which corresponds to the direction of the glacier advance, while the other two are perpendicular [18, 19].

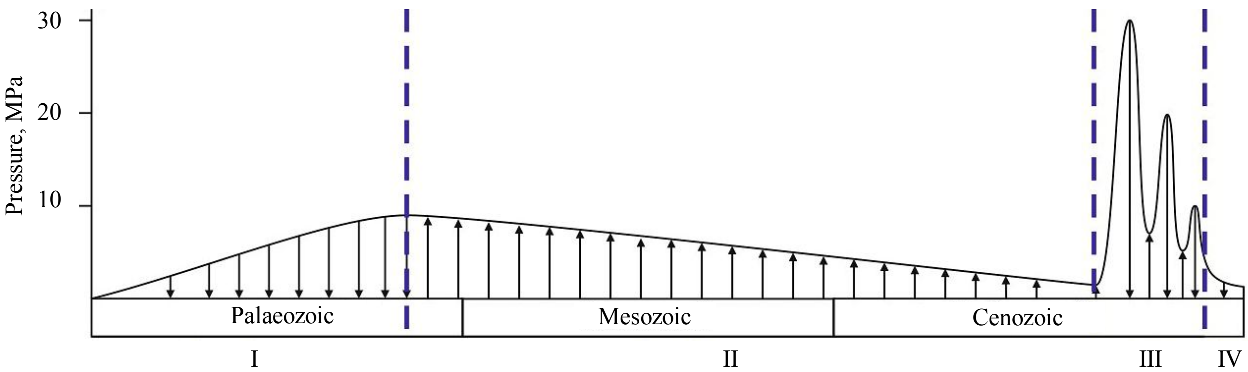

Fig.1. Schematic presentation of the time stages (I-IV) of the Vendian bedclay formation in the Saint Petersburg region

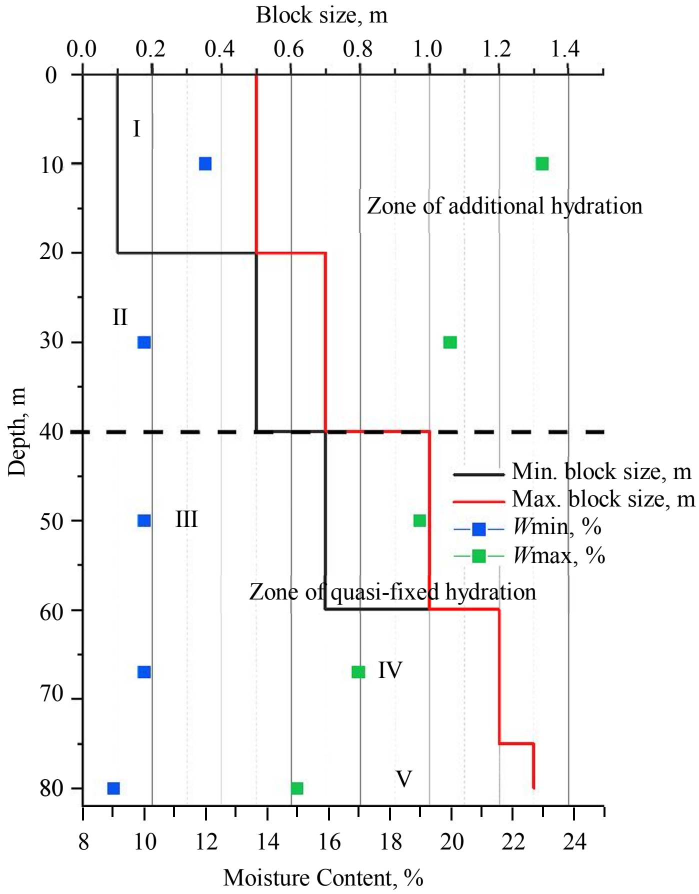

Fig.2. Engineering-geological zoning of the Upper Kotlin clays in the Saint Petersburg region

I-V – subzones

• During the fourth stage, the Holocene, the development of fissuring occurred mainly in relation to sediment unloading, current tectonic activity and, to a lesser extent, at local and site-related levels during underground excavations. Multi-factor studies of the history of geological development in the region, including processing of engineering-geological information from deep boreholes, made it possible to establish the main distinctive features of the in situ structure of bedclays, i.e. their zoning. At the same time, depending on the structural and tectonic conditions, it is necessary to separately assess the fissuring features of clays in the whole geological section outside the fault zones and within the buried valleys, where the expressed zoning is clearly disturbed. Thus, outside the zones of tectonic faults and buried valleys, the Upper Kotlin clay sequence was divided into five subzones (Fig.2) [15].

Irrespective of the foundation depth of a facility, the approach to analyzing the bedclays as a fissured-block medium has to be maintained. It should be noted that in areas of disjunctive dislocations, to which palaeovalleys are often confined, there is an increase in the intensity of macro- and micro-fissuring and, accordingly, a decrease in the size of blocks. According to the authors' calculations, up to 60 % of the territory of Saint Petersburg falls within the impact zone of the buried valleys, while calculations for individual islands show that the distribution of paleo trench cuts is not uniform (Table 1).

Table 1

The area of palaeovalleys in the river estuary (islands) of Saint Petersburg

Islands	Area, occupied by palaeovalleys, %
Admiralteysky (-1, -2 and Novo-)	75
Kazansky	67
Bezymianny	54
Petrovsky	52
Spassky	49
Vasilyevsky, Dekabristov	43
Petrogradsky, Aptekarsky, Hare, Kronverksky	26
Krestovsky	26
Kamenny	Outside of palaeovalleys
Kolomensky	
Matisov	

Outside the palaeovalleys, the depth to the top of the Upper Kotlin clays reaches 20-30 m. As more than half of the metropolitan area lies within their impact area, the use of Vendian sediments as a bearing strata for pile foundations of various buildings and facilities is considerably limited in terms of area. Thus, construction of apartment blocks in the Vasilievsky Residential Quarter in 2010 was one of the first cases when the Upper Kotlin clays were used as a bearing strata for the pile foundation of a multi-storey building (as recommended by R.E.Dashko). The need for such a solution was explained by the presence of morainic soils in the geological section that are characterized with a low bearing capacity as well as plastic deformation and failure due to a high level of organic contamination of abiotic and biotic origin. Since such glacial soils are widespread within the contaminated underground environment of the metropolitan area, and there exists an increase in the height of the building and the depth of its underground profile, the use of the Upper Kotlin clays as a bearing strata for pile foundations is becoming more and more common [15, 20].

Engineering-geological typification of the Upper Kotlin clays. The state as well as physical and mechanical properties of the Upper Vendian clays are analyzed and assessed both in terms of the section depth and area with account of their fissuring degree, which makes it possible to identify a number of typical sections with various degrees of complexity in development and utilization of the underground space (Fig.3).

The Upper Vendian formations are known to occur under the Quaternary strata in the northern and central parts of Saint Petersburg, as well as in the northern part of the Pre-Glint Lowland. Due to the specific engineering and geological conditions of the metropolitan city, these sediments have long been and are still widely used as the host media for tunnels and underground Metro stations, as well as deep sewage collectors. Currently, the use of the earth pressure balanced tunneling method allows most of the shallow stations and main line tunnels to be excavated in Quaternary glacial sediments.

The authors propose to distinguish two zones (outside and within the impact area of the buried valleys) and four subzones (Fig.3) depending on the degree of their fissuring that affects the engineering-geological properties of the clays, i.e. the “background” subzone (minimum fissuring), the tectonically faulted subzone, as well as the slope and valley bottom subzones within the palaeovalley zone. As the analysis was made primarily for conventional types of civil buildings, the depth of the piles was conventionally limited to 30-40 m. For unique facilities, however, this depth can be considerably higher [21].

The “background” subzone is the most favourable subzone both as the foundation for surface buildings and as the host medium for underground structures. It is characterized by the lowest degree of bedclay disintegration, zonal structure and a regular decrease in the moisture content, increase in density, strength and modulus of deformation with depth. Water permeability with account of background fissuring approximately ranges from 10^{-3} to 10^{-4} m/day, while in the upper zone with the highest

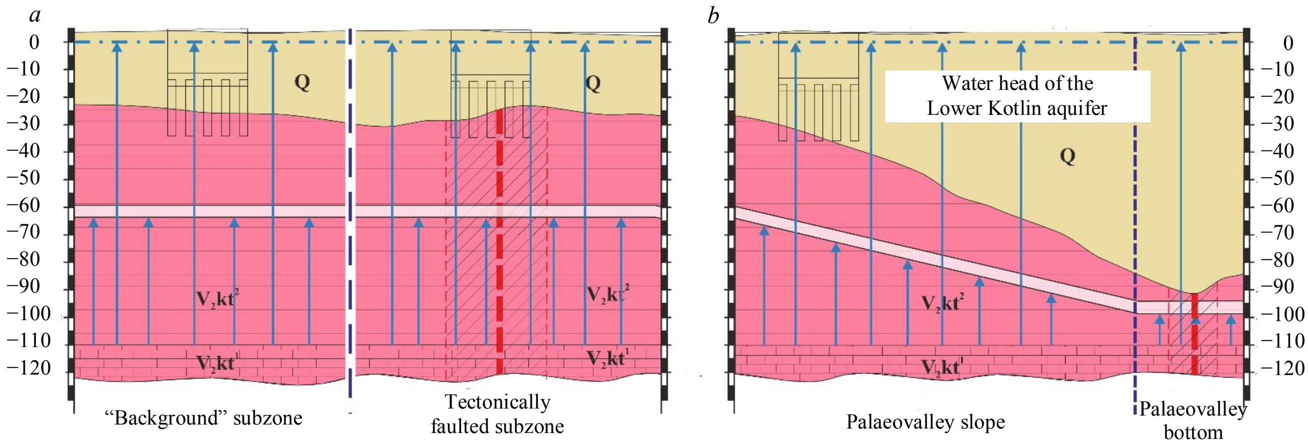

Fig.3. Schematic representation of Upper Vendian bedclays with the identified typical sections outside (*a*) and within (*b*) the buried valleys

fissuring the permeability coefficient can rise up to 10^{-2} m/day. For deep foundations of unique buildings, the local growth of bedclay fissuring as the result of the bored pile installation works has to be taken into account. The experience gained during the construction and initial stage of operation of a unique high-rise building in the city provides convincing evidence of active upward groundwater inflow from the Vendian aquifer system through the fissured upper Vendian clay strata and along the lateral surface of the piles [22]. However, at the designing stage of this building, the Upper Vendian clays were regarded as an absolutely impermeablelayer in accordance with the normative documents, and the complex impact of the high pressure water (with the head exceeding 100 m) was not taken into account. Sump pits were arranged in the underground story of the unique building, from which saline water is continually pumped out [22].

In the *tectonically faulted subzone,* the degree of fissuring is significantly higher, therefore zoning of changes in properties versus the depth is practically untraceable, and the strength and deformation properties are significantly lower than those in the "background" subzone. Processing of the survey data for the Okhta Centre construction site section showed that no change in the fissuring degree versus depth is observed, and no regular increase in strength of the Upper Kotlin clay samples was detected [10, 23, 24]. An important role in stability of both underground and surface structures built in this zone will be played by the increased permeability of the bedclays and consequently by the inflow of confined waters of the Vendian aquifer system.

Apart from hydrodynamic pressure on the bearing structures, groundwater will have a negative impact due to physical and chemical conditions (negative Eh values), chemical composition, i.e. sodium chloride water with mineralization of 3-5 g/dm^3, in rare cases up to 7 g/dm^3. In addition, these waters contain a rich microbial community: representatives of 115 bacterial genera were identified according to earlier indirect studies [25, 26], as well as based on the results of the 16S rRNA metagenomic analysis. Proteobacteria proved to be dominant, accounting for about 80 % of the total DNA isolated from the samples. Negative values of the redox potential determine the dominance of anaerobic bacteria taxa, i.e. the sulphate-reducing bacteria, which are responsible for the presence of hydrogen sulphide in these waters, and the ammonifying bacteria, which produce ammonia present in the aquifer as NH_4^+ ammonium ion. The presence of ferrobacteria, mainly the iron-reducing ones, which promote conversion of Fe^0 into Fe^{2+}, as well as reduction of Fe^{3+} into Fe^{2+}, promotes corrosion of steels. Anaerobic forms of hydrogen-generating bacteria, as well as optional groups, i.e. denitrifying and hydrogen oxidizing bacteria, are also present in the water. It should be stressed that the denitrifying bacteria contribute to formation of molecular nitrogen N_2. A lower quantity is observed for the optional aerobic forms, i.e. silicate and thionic bacteria. Presence of these microbial taxa makes it possible to predict the potential for biocorrosion of underground structures. Generation of hydrogen sulphide is quite dangerous for concrete and metals [9, 27, 28]. Active corrosion of steels and cast irons is caused by the ferrobacteria [29, 30], as well as the hydrogen-forming bacteria, which contribute to a sharp increase in steel brittleness (hydrogen charging) due to the generation of molecular hydrogen [31]. The silicate groups of bacteria utilize silica and destroy silicate minerals, including cements [32, 33], and the thionic bacteria produce sulphuric acid, which intensifies corrosion of concretes and metals [31].

This can be exemplified with the changes in chemical composition of water in the upper part of the Vendian aquifer system based on the data from hydrogeological monitoring boreholes drilled in the 10-meter thick top layer of the Upper Kotlin clays, which reflect transformation of the groundwater composition upon its interaction with reinforced concrete bored piles (Table 2). Piezometer P4, located downstream of the inflow, detects the effects of this active interaction, while Piezometer P8 installed outside the zone registers no infiltration flow.

DOI: 10.31897/PMI.2022.13

Journal of Mining Institute. 2022. Vol. 254. P. 180-190

Table 2

Water composition in the upper part of the Vendian aquifer system based on data from monitoring boreholes in the unique building

Indicator	Indicator values by piezometers		Indicator	Indicator values by piezometers	
	P4	P8		P4	P8
Eh, mB (in situ)	−154.2	Not ident. −35.4 (background)	SO_4^{2+}, mg/dm^3	54	< 10
pH (in situ)	10.5	7.8	NO_2^-, mg/dm^3	0.09	< 0.02
Na^+, mg/dm^3	722	716	NO_3^-, mg/dm^3	0.23	< 0.1
K^+, mg/dm^3	44	31	Silicic acid (by Si content), mg/dm^3	0.34	0.41
Ca^{2+}, mg/dm^3	14	85	Chemical oxygen demand, mgO/dm^3	460	230
Mg^{2+}, mg/dm^3	8.5	85	Permanganate oxygen consumed, mgO/dm^3	76	13
NH_4^+, mg/dm^3	1.4	3.6	Biochemical oxygen demand$_5$, mgO/dm^3	79	43
Fe^{2+}, mg/dm^3	0.053	0.06	Petroleum products, mg/dm^3	0.25	0.27
Fe_{tot}, mg/dm^3	9.1	13.2	Al, mg/dm^3	0.20	0.25
HCO_3^-, mg/dm^3	306	233	F^-, mg/dm^3	0.86	0.72
Cl^-, mg/dm^3	992	1390	Solids content, mg/dm^3	2050	2470

As it follows from analyzing data in Table 2, a significant decrease in the Eh value is observed, which is associated with increasing organic content in the water due to disintegration of polymer concrete in piles and plasticizing agents in concrete, which are used as its hardening accelerators. This assumption is confirmed by a two-fold increase in the Chemical Oxygen Demand and almost a six-fold increase in the permanganate oxygen consumed. Leaching of concrete is reflected in the content of calcium and magnesium ions. Alkaline earth elements are present in water as fine suspensions of $Ca(OH)_2$ and $Mg(OH)_2$ at high pH values (in this case over 10). When sampling water from P4, a slightly soluble gas release was observed. Based on the results of metagenomic analysis, the presence of molecular nitrogen and hydrogen can be assumed. In addition, as the result of active interaction between groundwater and piles, an almost two-fold increase of Biochemical Oxygen Demand$_5$ was detected, which is associated with increased activity of aerobic micro-organisms.

The slope and bottom subzones of the buried valley often occupy a fairly large area, as in some cases the paleo trench cuts can be as deep as 90 m with the relatively small slope angles of the valley sides up to 18°. This zone is characterized with higher fissuring, also due to the existence of ancient landslides, which development took place at the same time as the formation of the river valley. In addition, the change of the top of paleo formation position in space and the gradual increase in the thickness of quaternary deposits should be taken into account, which imposes restrictions on construction of surface facilities in this zone. Construction and operation of underground structures in this zone is complicated by higher fissuring, which predetermines the growth of hydrodynamic pressure of the Vendian aquifer system depending on the position of tunnels in relation to its top.

The subzone of the buried valley bottom – is the most difficult in terms of construction and subsequent operation of underground structures. The surveys carried out in a number of underground main line tunnels showed

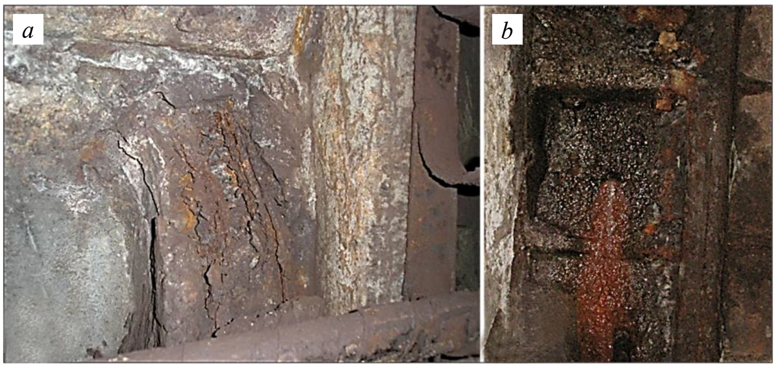

Fig.4. Corrosion of tunnel lining made of reinforced concrete (*a*) and cast iron (*b*) (photo by E.Yu.Shatskaya)

that in this zone the hydrodynamic action of the Vendian aquifer system is greatest due to decreasing clay thickness (Fig.3) and increasing head gradients; in some cases, due to back pressure, a reduction in subsidence deformations or even tunnel uplifts are observed. The active filtration of such aggressive waters contributes to destruction of waterproofing layers and degradation of lining materials due to active biocorrosion of reinforced concrete and cast iron [34, 35] (Fig.4).

It should be noted that when the top of the clays occurs at a depth less than 30-40 m, contamination of the upper part of the geological section, including microbial contamination, should be taken into account, whereas the presence of a tectonic fault dramatically increases permeability of the clays due to fissuring and, consequently, the depth of contamination. The city's location within the river estuary, the low ground surface elevations, widespread swamps in times before Saint Petersburg was built, as well as the long development period of this territory (over five centuries) caused contamination of the underground environment to a considerable depth and area [36].

The fissured strata of bedclays has the capacity to accumulate microorganisms on the fissure surfaces, which has been repeatedly confirmed by the results of their studies in various districts of the metropolitan city. Studies of the total microbial protein using the Bradford protein assay made it possible to determine that its content in the upper zone of the Vendian clays exceeds 1000 μg/g in the Admiralteisky, Primorsky, Vasileostrovsky and other districts. At the base of Saint Isaac's Cathedral, where bedclays occur at the depth of more than 40 m (a slope of the buried valley), the total microbial protein content was over 1600 μg/g, while its background values do not exceed 30 μg/g.

Uniaxial compression tests as well as single-plane unconsolidated undrained (UU) shear tests carried out on samples of the Upper Kotlin clays from the Teatralnaya Square (the development of this territory started over 300 years ago), in spite of their considerable density (2.09-2.17 g/cm^3), produced very low strength and deformation values, i.e. the angle of internal friction decreased to the minimum level (0-2°), internal cohesion in the sample (c_o) was 0.18 MPa (without taking fissuring into account), the deformation modulus was 11 MPa. In uniaxial compression tests, the specimens showed the plastic and near plastic deformation and fracture patterns. Considering that the structural loosening factor by G.L.Fisenko (λ) reaches 0.5, the value of massif cohesion (c_m) with account of fissuring decreases down to 0.09 MPa and less ($c_m = \lambda c_o$).

Transformation of the Upper Kotlin clays as the result of their interaction with waters of the Vendian aquifer system. As the saline water flows through the fissured clay strata, it affects not only the subsurface structures, but also the clay blocks. The cumulative effect of the saline water flow process on the Vendian clays has been modelled by the authors in laboratory conditions. For this purpose, we used the Upper Kotlin Vendian clays sampled from a depth of about 70 m from the face of an auxiliary underground excavation under construction in south-west part of Saint Petersburg outside the tectonic faults, and water of the Vendian system as the interacting solution. No swelling or compaction of the samples was allowed during the test, which was controlled by pressure selection. An anaerobic environment was modelled similar to the one observed in situ in the aquifer, with the water in the packers being periodically refreshed. Slimy orange and brown iron oxide films were formed on the water surface during the test, while large amounts of black suspended hydrotroilite were observed forming in the water. Upon completion of the test, the swelling (back) pressure was determined, and the clay samples were tested in Unconsolidated Undrained (UU) state using a single-plane shear test apparatus. After a long-term interaction of clays with the water, their particle size distribution was examined using the laser diffraction method on the LA-950 Laser Diffraction Particle Size Distribution Analyzer, as well as some other physical property parameters (moisture content and density).

A part of the clay samples before and after the test was given for microbiological analysis by inoculation of medium. After 80 days of physical modelling of the interaction process between waters of the Vendian system and blocks of the Upper Kotlin clays, a change in colour of the samples to greyish blue was visually recorded; the samples were covered with a black hydrotroilite film which quickly became oxidized in the air. Water in the packers had a persistent smell of hydrogen sulphide, the samples slightly smelt of asphalt.

Outcome of the experiment. Physical properties of the clays remained practically unchanged upon the test completion, i.e. the moisture content increased from 13.6 % to 14.7 % and the samples preserved their physical state (solid liquidity index). Density of the clays remained unchanged at 2.21 g/cm^3. Studies of the particle size distribution in the Upper Kotlin clay samples showed a slight increase in the clay and fine silt fractions: < 0.002 mm (40.49 % before the test and 42.39 % upon the test); 0.002-0.01 mm (42.45 and 50.26 %); 0.01-0.05 mm (16.90 and 7.03 %); > 0.05 mm (0.16 and 0.32 %).

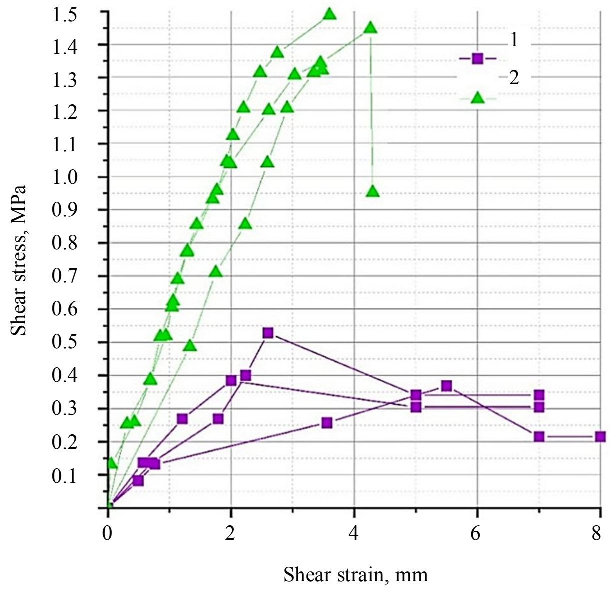

Fig.5. Patterns of changes in shear resistance vs. shear strain

1 – Upper Kotlin clays after the test;
2 – unchanged Upper Kotlin clays

Anisotropy of the swelling pressure in the Upper Kotlin clays was observed in horizontal (along the bedding) and vertical (perpendicular to the bedding) directions: 0.11 and 0.24 MPa respectively, which indicates the impossibility of closing and healing the fissures during water infiltration through the fissured clay strata. The swelling anisotropy factor is 2.1 on average.

The most significant changes were observed for shear resistance values, i.e. within a short period of time cohesion of samples decreased by three times (from 1.06 to 0.35 MPa according to the single-plane unconsolidated undrained (UU) shear tests data), the angle of internal friction decreased by 3 degrees (from 14 to 11 degrees). The deformation patterns of specimens before and after interaction with saline waters of the Vendian aquifer are shown in Fig.5, the change in the failure pattern of the samples indicates a transformation in the nature of structural bonds.

Comparison of the results of microorganisms isolation from the Upper Kotlin clay samples before and after 80 days of their interaction with waters of the Lower Kotlin aquifer demonstrated a significant increase in the number of most groups of microorganisms under the influence of groundwater (Table 3). The following bacterial taxa were identified in the samples based on inoculations on nutrient media: sulphate-reducing, ammonifiers, ferrobacteria, (mainly iron-reducing), as well as actinomycetes and silicate bacteria.

Upon analyzing the seeding materials, as well as the organoleptic changes in the clay samples, it can be concluded that the main microbial activity is caused by the sulphate-reducing bacteria, as well as the iron-reducing ones. Their activity is associated with the emergence of hydrogen sulphide and formation of hydrotroilite, also due to transformation of siderite, a small amount of which is registered in these clays. The observed intensification of ammonifiers activity can be accompanied by emission of ammonia, which is found in the aqueous media as NH_4^+ ions. The development of the “asphalt” smell in the samples is attributed to activities of actinomycetes, which play a notable role in formation of new organic compounds due to their ability to utilize a wide range of carbon and nitrogen sources. The silicate bacteria contribute to degradation of silicate minerals in clays and concretes.

DOI: 10.31897/PMI.2022.13

Table 3

Results of bacteriological analysis of samples before and after their interaction with waters of the Vendian aquifer system

Sample	Silicate bacteria	Actinomycetes	Ferrobacteria	Ammonifiers	Sulphate-reducing bacteria
N 1 (before the test)	10^2	10^3	10^3	10^2	10^5
N 2 (upon the test)	10^4	10^5	10^4	10^4	Over 10^6

Discussion of results. Analyzing the obtained data, conclusions can be made regarding the impact of the interaction between the saline water of the Vendian aquifer with the Upper Kotlin clays on the clay composition, condition and properties as the result of the experiment.

- Changes in the particle size distribution, i.e. increasing of the clay and fine silt fractions, are caused by dispersion of micro-aggregates ranging from 0.01 mm to 0.05 mm in size due to chemical action of sodium waters and biochemical activity of ammonifying bacteria (NH_4^+ и Na^+ cations are attributed to dispersing agents).
- A slight increase in the moisture content is related to reaching the state of complete water saturation and increasing content of fine fractions.
- Adverse changes in properties are observed in terms of shear resistance. A threefold decrease in cohesion is mainly caused by biochemical activities of microorganisms: transformation of the strong structural bonds was caused by destruction of silicates by the bacteria of the same name, as well as the conversion of cementing siderite into hydrotroilite as the result of the sulphate- and iron-reducing bacteria activity.

Conclusions

1. The paper examines formation of the fissured Upper Kotlin clays of the Upper Vendian Period based on the analysis of time stages in formation of these sediments during the periods of progressive and regressive lithogenesis in the Saint Petersburg region, including the action of the tectonic processes, physical weathering during the continental stage in the development of the territory, cyclic loads during glacial periods as well as the action of glaciotectonics.

2. In situ zonal structure of clays was established based on complex research and processing of engineering-geological information. Two zones and four subzones are identified, which differ in the degree of disintegration according to the block size, as well as the moisture content and density. It is noted that the zonal structure of the bedclays exists only outside the tectonic fault zones. Within the impact zone of disjunctive dislocations, including the areas of buried valleys, the zonal structure of the strata in terms of fissuring (the block nature) is disrupted. Typification of specific features of the Upper Kotlin clay formation was performed for the territory of Saint Petersburg with account for the relative size of the area occupied by buried valleys in the island part of the city.

3. Taking into account the fissured character of the Upper Vendian bedclays, the consequences of the inflow of high-pressure saline water of the Vendian aquifer system through the relatively impermeable stratum are considered with respect to hydrodynamic pressure development, impact of physical and chemical factors, chemical composition and their biochemical properties. Examples of destruction of cast-iron and reinforced concrete tunnel linings are given based on previously published works, the tendencies in disintegration of the bored foundations piles of a unique high-rise building are described, and the adverse transformation of the Upper Kotlin clay blocks upon their interaction with the saline waters of the Vendian aquifer system is also assessed. Regularities in changes of the particle size distribution have been established, as well as the microbiological damage

of clays, and a significant decrease in their shear resistance as the result of transformation in the character of structural bonds.

4. The results of a multi-year studies of the Upper Kotlin clays that are used as either a medium or foundation for structures in the Saint Petersburg region can be recommended for engineering surveys as well as for designing of surface and underground facilities, particularly the unique ones, to assess the impact of saline waters of the Vendian aquifer system on the long-term stability of structures and structural materials.

REFERENCES

1. Bezrodnyi K.P., Lebedev M.O. Regarding stresses from formation pressure on tunnel linings in tunneling. *Journal of Mining Institute*. 2017. Vol. 228, p. 649-653. DOI: 10.25515/PMI.2017.6.649

2. Lavrenko S.A., Korolev I.A. Research into the process of Cambrian clay disintegration by cutting when driving underground excavations of St. Petersburg Metro. *Gornyi Zhurnal*. 2018. N 2, p. 53-58. (In Russian). DOI: 10.17580/gzh.2018.02.08

3. Yungmeyster D.A., Isaev A.I. Rationale for the parameters of bore hammer for tunneling the service roadways in cambrian clays. *Journal of Industrial Pollution Control*. 2017. Vol. 33. Iss. 1, p. 920-925.

4. Yerzova V.A., Rumynin V.G., Nikulenkov A.M., Vladimirov K.V., Sudarikov S.M. Prediction of radionuclide migration in ground waters within the impact zone of construction drainage system of the Leningrad-2 Nuclear Power Plant. *Journal of Mining Institute*. 2022, p. 1-18 (Online first). DOI: 10.31897/PMI.2022.27

5. Gusev V.N., Maliukhina E.M., Volokhov E.M. et al. Assessment of development of water conducting fractures zone in the massif over crown of arch of tunneling (construction). *International Journal of Civil Engineering and Technology* (*discontinued*). 2019. Vol. 10. N 2, p. 635-643.

6. Protosenya A.G., Verbilo P.E. Research of compression strength of fissured rock mass. *Journal of Mining Institute*. 2017. Vol. 223, p. 51-57. DOI: 10.18454/PMI.2017.1.51

7. Protosenya A.G., Karasev M.A., Verbilo P.E. The prediction of elastic-plastic state of the soil mass near the tunnel with taking into account its strength anisotropy. *International Journal of Civil Engineering and Technology*. 2017. Vol. 8. Iss. 11, p. 682-694.

8. Volokhov E.M., Kireeva V.I. Analysis of the results of field studies of geomechanical processes in construction of large transport tunnels with the use of a mechanized tunnelboring complex with work face earth pressure balance in the special conditions of voids compensation in the rock massif. *ARPN Journal of Engineering and Applied Sciences*. 2017. Vol. 12. Iss. 20, p. 5811-5821.

9. Chaminé H.I., Afonso M.J., Trigo J.F. et al. Site appraisal in fractured rock media: coupling engineering geological mapping and geotechnical modelling. *European Geologist Journal*. 2021. Vol. 51, p. 30-38. DOI: 10.5281/zenodo.4948771

10. Davidson J., Castelletti M., Torres I. Pile driving prediction for monopile foundations in London clay. Proceedings of the XVII ECSMGE, 1-6 September 2019. Reykjavík, Iceland. ECSMGE, 2019, p. 1-9. DOI: 17ecsmge-2019-Y-XXXX

11. Rosone M., Ziccarelli M., Ferrari A., Farulla C.A. On the reactivation of a large landslide induced by rainfall in highly fissured clays. *Engineering Geology*. 2018. Vol. 235, p. 20-38. DOI: 10.1016/j.enggeo.2018.01.016

12. Vitone C., Guglielmi S., Pedone G., Cotecchia F. Effects of micro-to meso-features on the permeability of fissured clays. *Géotechnique Letters*. 2019. Vol. 9. Iss. 4, p. 369-376. DOI: 10.1680/jgele.18.00237.

13. Podkovyrov V.N., Kotova L.N. Lithogeochemistry and formation conditions of Upper Vendian and Lower Cambrian sediments in the northwest part of the Baltic monocline. *Vestnik of Saint-Petersburg University. Earth Sciences*. 2020. Vol. 65. N 3, p. 600-619. (In Russian). DOI: 10.21638/spbu07.2020.310

14. Bazhin N.P., Petrov V.A., Kartashov Yu.M., Bazhenov A.I. Results of studying physical and mechanical properties of Cambrian clays. *Formation pressure, displacement of rocks and methodology of mine surveying work: Proceedings of Research Institute of Mine Geomechanics and Surveying* (*VNIMI*). 1964. Iss. LIII, p. 49-63. (In Russian).

15. Dashko R.E. Engineering geological analysis and assessment of water-saturated clayey formations as structure bases. St. Petersburg: Institut "Georekonstruktsiya", 2015, p. 382. (In Russian).

16. Lomtadze V.D. Physical and mechanical properties of Lower Cambrian clays of the north-western margin of the Russian Platform. *Journal of Leningrad Mining Institute*. 1958. Vol. 34 (22), p. 154-188. (In Russian).

17. Bagrintseva K.I. Fracturing of sedimentary rocks. Moscow: Nedra, 1982, p. 256. (In Russian).

18. Korobko A.A. Engineering-geological analysis and assessment of conditions for the construction and operation of facilities of various applications within the Pre-Glint Lowland: Saint Petersburg region: Avtoref. dis. … kand. geol.-mineral. nauk. St. Petersburg: Natsional'nyy mineral'no-syr'evoy universitet "Gornyy", 2015, p. 20. (In Russian).

19. Feeser V. On the mechanics of glaciotectonic contortion of clays. *Glaciotectonics: forms and processes. Various meetings of the glaciotectonics work group*. 1988, p. 63-76.

20. Demenkov P.A., Goldobina L.A., Trushko O.V. Method for Forecast of Surface Deformation During Excavation Operations in Restraint Urban Conditions Using The Slurry Trench Technique. *Journal of Mining Institute*. 2018. Vol. 233, p. 480-486. DOI: 10.31897/PMI.2018.5.480

21. Ilyukhina E., Lakhman S., Miller A., Travush V. Structures of the high-rise building "Lakhta center" in Saint-Petersburg. *International Journal for Computational Civil and Structural Engineering*. 2019. Vol. 15. N 3, p. 14-39. DOI: 10.22337/2587-9618-2019-15-3-14-39

22. Travush V.I., Shulyat'ev O.A., Shulyat'ev S.O. et al. Analysis of the results of geotechnical monitoring of "Lakhta Center" Tower. *Soil Mechanics and Foundation Engineering*. 2019. Vol. 56. N 2, p. 98-106. DOI: 10.1007/s11204-019-09576-9

23. Zhukova A.M. Geotechnical engineering and hydrogeological specifics of estimate high-rise buildings construction and operation conditions (in terms of local zone on the right bank of Neva river). *Journal of Mining Institute*. 2010. Vol. 186, p. 13-17. (In Russian).

24. Zhukova A.M. Engineering-geological justification for construction of high-rise buildings in St. Petersburg: Avtoref. dis. … kand. geol.-mineral. nauk. St. Petersburg: Sankt-Peterburgskiy gosudarstvennyy gornyy universitet, 2011, p. 20. (In Russian).

25. Kotyukov P.V. Engineering-geological and hydrogeological support of operational reliability of underground transport structures in St. Petersburg (using the case of the Elizarovskaya – Lomonosovskaya and the Obukhovo – Rybatskoe main line tunnels): Avtoref. dis. … kand. geol.-mineral. nauk. St. Petersburg: Sankt-Peterburgskiy gosudarstvennyy gornyy institut im. G.V.Plekhanova, 2010, p. 20. (In Russian).

26. Shatskaya E.Yu. Engineering-geological justification of conditions for construction and operation of underground transport structures within the historical part of St Petersburg: Avtoref. dis. … kand. geol.-mineral. nauk. St. Petersburg: Sankt-Peterburgskiy gosudarstvennyy gornyy institut im. G.V.Plekhanova, 2010, p. 20. (In Russian).

27. Dashko R.E., Kotiukov P.V. Fractured clay rocks as a surrounding medium of underground structures: The features of geotechnical and hydrogeological assessment. ISRM European Rock Mechanics Symposium – EUROCK 2018, 22-26 May 2018, St. Petersburg, Russia. OnePetro, 2018, p. 241-248. DOI: 10.1201/9780429462078-25/

28. Hilpmann S., Drobot B., Steudtner R. et al. Uranium (VI) reduction by a sulphate-reducing microorganism in Opalinus Clay pore water. *Tage der Standortauswahl*. 2021, p. 147.

29. Emerson D. The role of iron-oxidizing bacteria in biocorrosion: a review. *Biofouling*. 2018. Vol. 34. Iss. 9, p. 989-1000. DOI: 10.1080/08927014.2018.1526281

30. Kalajahi S. T., Rasekh B., Yazdian F. et al. Corrosion behaviour of X60 steel in the presence of sulphate-reducing bacteria (SRB) and iron-reducing bacteria (IRB) in seawater. *Corrosion Engineering, Science and Technology*. 2021. Vol. 56. Iss. 6, p. 543-552. DOI: 10.1080/1478422X.2021.1919840

31. Loto C.A. Microbiological corrosion: mechanism, control and impact – a review. *The International Journal of Advanced Manufacturing Technology*. 2017. Vol. 92. Iss. 9, p. 4241-4252. DOI: 10.1007/s00170-017-0494-8

32. Efe D., Ertan B., Savas M., Orhan F. Isolation and Identification of Bacteria with silicium dissolution ability from boron clay. *International Journal of Scientific & Engineering Research*. 2019. Vol. 10. Iss. 9, p. 26-29.

33. Fomina M., Skorochod I. Microbial Interaction with Clay Minerals and Its Environmental and Biotechnological Implications. *Minerals*. 2020. Vol. 10. Iss. 10. N 861. DOI: 10.3390/min10100861

34. Černoušek T., Shrestha R., Kovářová H. et al. Microbially influenced corrosion of carbon steel in the presence of anaerobic sulphate-reducing bacteria. *Corrosion Engineering, Science and Technology*. 2020. Vol. 55. Iss. 2, p. 127-137. DOI: 10.1080/1478422X.2019.1700642

35. Chen H., Kimyon Ö., Ramandi H.L. et al. Microbiologically influenced stress corrosion cracking responsible for catastrophic failure of cable bolts. *Engineering Failure Analysis*. 2021. Vol. 131. N 105884. DOI: 10.1016/j.engfailanal.2021.105884

36. Kovyazin V.F., Skachkova M.E., Diachkova I.S. Historical and cultural assessment of urbanized territories as part of cadastral, land use planning and evaluation activities. *Geodesy and Cartography*. 2020. N 12, p. 57-62. (In Russian). DOI: 10.22389/0016-7126-2020-966-12-57-62

***Authors*: Regina E. Dashko,** *Doctor of Geological and Mineralogical Sciences, Professor, https://orcid.org/0000-0002-2469-0910* (*Saint Petersburg Mining University, Saint Petersburg, Russia*), **Georgiy A. Lokhmatikov,** *Postgraduate Student, kriptoforan@gmail.com, https://orcid.org/0000-0001-9134-3022* (*Saint Petersburg Mining University, Saint Petersburg, Russia*).

The authors declare no conflict of interests.