

## Article

# Scientific-Practical Enhancement Principles for the Long-Term Stability of Cultural Heritage Objects through a Multi-Component Underground Space Analysis

Regina E. Dashko  and Angelina G. Karpenko \* 

Department of Hydrogeology and Engineering Geology, Empress Catherine II Saint Petersburg Mining University, 199106 Saint Petersburg, Russia; dashko\_re@pers.spmi.ru

\* Correspondence: ange.karpencko2017@yandex.ru

**Abstract:** This article presents approaches for enhancing engineering-geological and geotechnical research for the restoration and reconstruction projects of cultural heritage objects in St. Petersburg's historical center. According to the Venice Charter, an interdisciplinary approach is recommended for developing a preservation program for cultural heritage objects. The authors consider the underground space as a multi-component system, where soils are a host medium for underground water with specific composition, complex physicochemical and biochemical conditions, the presence and vigorous activity of microorganisms, gases of various origins, and underground bearing and enclosing structures. The last of these components is crucial for the long-term stability of historical and cultural objects, as they interact in complex with water-saturated soils and microorganisms. This approach is not to be found in Russian cultural heritage preservation regulations. In engineering-geological and geotechnical research, multi-component underground space should be studied at the regional, local, and object levels. Assessing redox conditions in the underground environment is crucial for understanding the state of its components. Moreover, this can trigger hazardous processes such as changes in the stress-strain state and unconsolidation of the soil layer due to the generation of low-solubility gases and biocorrosion of ancient and modern building materials, causing premature destruction. Recommendations are provided for carrying out engineering-geological and geotechnical research based on cultural heritage objects, considering the multi-component underground space and features of its geoenvironmental state due to the long-term contamination and transformation of its components.

**Keywords:** preservation of cultural heritage objects; underground space; contamination; microorganisms' activity



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## 1. Introduction

At present, the preservation of cultural heritage objects, ensuring their long-term stability and safe functioning, is a global challenge that requires a non-trivial approach to its solution. The world-renowned artist and public figure, N.K. Roerich, made a significant contribution to this issue. He presented a report on the protection of cultural heritage to the world community in 1928, which marked the beginning of long-term study by delegations from more than 20 countries to create the International Treaty for the Protection of Artistic and Scientific Institutions and Historic Monuments (Roerich Pact) that was adopted on 15 April 1935. The next stage in international study on the preservation of cultural heritage objects was the development of the Venice Charter for the Conservation and Restoration of Monuments and Sites (1964), which was based on the Athens Charter (1931) of the French architect Le Corbusier. For the first time, the Venice Charter, which consisted of 16 articles, emphasized the need for an interdisciplinary approach in the conservation and restoration of architectural monuments: “The conservation and restoration of monuments

must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage” (Article 2).

In the restoration and reconstruction of cultural heritage objects, specialists of various profiles are involved, such as architects, restorers, construction engineers, geotechnicians, engineering geologists, hydrogeologists, etc., but the interactions between them are often formal or practically non-existent. Through the organization of the International Conference on Soil Mechanics and Geotechnical Engineering, specialists in various fields of construction, building design, engineering geology, and hydrogeology have had the opportunity since the late 20th century to share their experiences in preserving cultural heritage objects in different countries. The idea of creating a conference section devoted to ensuring the long-term stability of architectural and historical monuments belongs to French and Italian specialists in soil mechanics and geotechnics, primarily J. Kerisel and A. Croce. They proposed the establishment of a technical committee for the preservation of historical attractions within the International Society for Soil Mechanics and Geotechnical Engineering. Among foreign geotechnical and geomechanical engineers, the following have worked and are working on this issue: R. Jappelli, C. Viggiani [1], J.B. Burland [2], Ch. Tsatsanifos, Pr.N. Psarropoulos, S. Hemeda [3,4], Y. Iwasaki [5,6], and others. Notably, Russian specialists in the fields of construction, soil mechanics, geotechnics, and engineering geology have made significant efforts to preserve cultural heritage objects in Russia, including in Leningrad—Saint Petersburg. Among these specialists are N.P. Nikitin (D. Arch.), B.D. Vasilyev (D. Eng. Sc., Prof.), V.A. Florin (D. Eng. Sc., Prof.), A.G. Shashkin (D. Sc. in Geology and Mineralogy) [7–9], V.M. Ulitsky (D. Eng. Sc., Prof.) [10], S.N. Sotnikov (D. Eng. Sc., Prof.) [11,12], and others. E.M. Pashkin (D. Sc. in Geology and Mineralogy, Prof.) has made a significant contribution to the preservation of monasteries, cathedrals, and churches in ancient Russian cities [13,14].

Engineering-geological surveys and research precede the development of restoration or reconstruction projects for historical and cultural objects. (The issue of restoring architectural and historical monuments, primarily monasteries, cathedrals, and churches from the 17th to the early 20th centuries, is a very thorny and relevant question for Russia. During the period of Soviet power and its antireligious policies, more than 70,000 religious objects were destroyed. Striking examples include the Cathedral of Christ the Savior in Moscow, which was blown up and dismantled in 1931, and in its place the largest outdoor pool in the USSR and one of the largest in the world was built. The Cathedral of Christ the Savior was restored only in 2000. A number of monasteries, cathedrals, and churches ceased to perform their basic functions and were converted for various household needs up until the end of the 20th century). In the Russian regulatory-technical base, a clear distinction is made between the content and concept of engineering-geological surveys and engineering-geological research. In contrast to engineering-geological surveys, the implementation of which is regulated by relevant regulatory documents, engineering-geological research is characterized by the “originality” and “non-standard” of the methodology used in field and laboratory studies, as well as by the analysis of the results obtained. Original and non-standard research methods should be used in field and laboratory conditions when researching primarily underground microorganisms from the perspective of their activity and negative impact on other components of the underground space: soils, underground water, the generation of biochemical gases, and the development of natural–technogenic processes.

This article examines the theoretical and scientific-practical aspects of implementing an interdisciplinary approach in conducting engineering-geological and geotechnical research for the development of restoration or reconstruction projects for cultural heritage objects using the historical center of Saint Petersburg. There are more than 9000 historical and cultural objects within its boundaries: palaces, cathedrals, churches, museums, theaters, and monuments, as well as residential and administrative buildings that have been under UNESCO protection since 1990.

## 2. Methodology, Methods, and Materials for Engineering-Geological and Geotechnical Research

At present, there is no unified methodology for conducting engineering-geological and geotechnical research to analyze the long-term stability of architectural and historical monuments, inspecting them, and developing reconstruction and restoration projects for cultural heritage objects while considering the specifics and complexity of underground space. Based on the ideas of the Venice Charter, which emphasized the need for an interdisciplinary approach, the underground space in historical districts of a megapolis should be analyzed as a multi-component system in which soils serve as a containing medium for the following:

- underground water.
- microorganisms.
- gases of various geneses, solubilities, and aggressiveness.
- underground bearing and enclosing structures of buildings and constructions, which have complex interactions with the aforementioned components.

Engineering-geological research on soil mechanical properties was conducted in specialized laboratories via licensed triaxial compression devices and field methods. Our research utilized field equipment, including vane tests for soft clay soils. The chemical composition of underground water was studied with an expanded list of elements and compounds in both field and laboratory conditions, following the regulatory documents and requirements of the Russian Federation. Particular attention was given to measurements of the oxidation–reduction potential  $E_h$ , which is not typically used in engineering-geological and geotechnical practices. In most cases, the determination of the hydrogen index pH was conducted directly in the boreholes under field conditions. A WaterLiner WMM-81 m with an external plastic pH electrode, WaterLiner EPHP-10, and an external immersion ORP electrode, WaterLiner ERPL-30, was employed to measure these parameters. Selective electrodes have also been used to detect unstable components such as hydrogen sulfide  $H_2S$ , sulfates  $SO_4^{2-}$  (ion-selective electrode XC-SO4-001), and ammonium  $NH_4^+$  (ion-selective electrode XC-NH4-001). Special attention has been given to the content of organic compounds of abiotic and biotic origin, as the presence of these compounds determines the physicochemical conditions in the underground space, which in turn dictates the state of its components.

The prediction of changes in the stress–strain state of the soil layer should be based on not only traditional principles of soil mechanics but also on consideration of the development of physical–chemical and biochemical processes in the underground space. They are related to the activity of certain physiological groups of microorganisms and the specifics of contamination of the underground space due to natural and technological sources. Studies of microbial infestations in soils, underground water, and construction materials of underground structures have been conducted for more than 30 years via direct microbiological methods, such as cultivation on nutrient media, which since 2018 have supplemented the results of metagenomic analysis of 16S ribosomal ribonucleic acid (16S rRNA). Microbiological studies are conducted via modern diagnostic equipment at the Research Resource Center for Molecular and Cell Technologies of Saint Petersburg State University. The identification of microorganisms in underground water samples was performed on the basis of the analysis of the nucleotide sequence of the 16S rRNA gene. Primers from the metagenomic-library-prep-guide protocol were used. This study investigated microbial activity indirectly by analyzing the microbial mass content, as determined by M. Bradford, which led to conclusions about the negative changes in clay soil strength and sand permeability over time. To observe the presence of microorganisms in soils and the degradation of construction materials (concrete), scanning and polarization electron microscopy were utilized.

The biocorrosion of structural materials from underground microorganisms' activity is a little-studied process for Russian specialists and is not considered when analyzing the

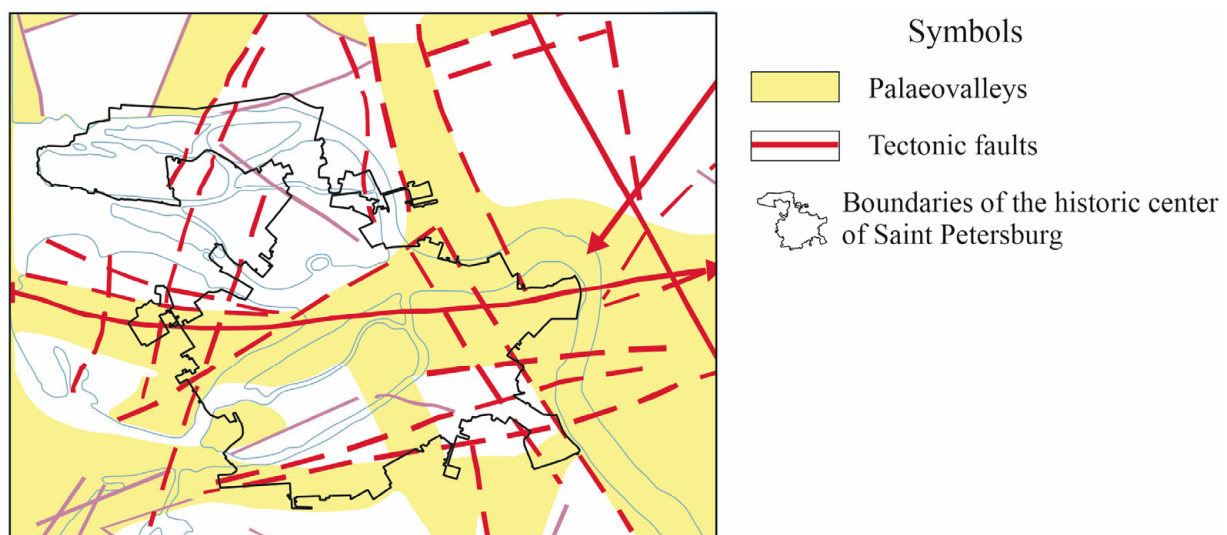
reasons for destruction of underground structures for various purposes. The exceptions are wooden structures, for which usually mycological studies are conducted.

The carrying out of engineering-geological and geotechnical research for creating reconstruction or restoration projects of architectural and historical monuments is limited only to the foundation zone of the object and its outlines. The authors consider that when developing a program for engineering-geological and geotechnical research on a multi-component underground space, a phased approach to its study at the regional, local, and object levels is necessary. The region's and local area's features determine the complexity and specificity of the foundation conditions, directly affecting the investigated object's long-term stability.

### 3. Results

#### 3.1. Results of Underground Space Research at the Regional Level

The regional-level assessment of the underground space in the historical center is recommended to start with the structural–tectonic conditions of the megapolis. St. Petersburg's territory is characterized by northwest, northeast, sublatitudinal, and submeridional regional faults, along with less extensive local disjunctive dislocations in the crystalline bedrock. These faults extend into the pre-Quaternary sedimentary strata of the Upper Vendian, leading to their disintegration and influencing water and gas permeability, strength, and stability (Figure 1) [15–17].



**Figure 1.** Structural–tectonic framework within the historical center of Saint Petersburg (based on data by L.G. Kabakov, E.K. Melnikov, B.G. Dvernitsky) [18].

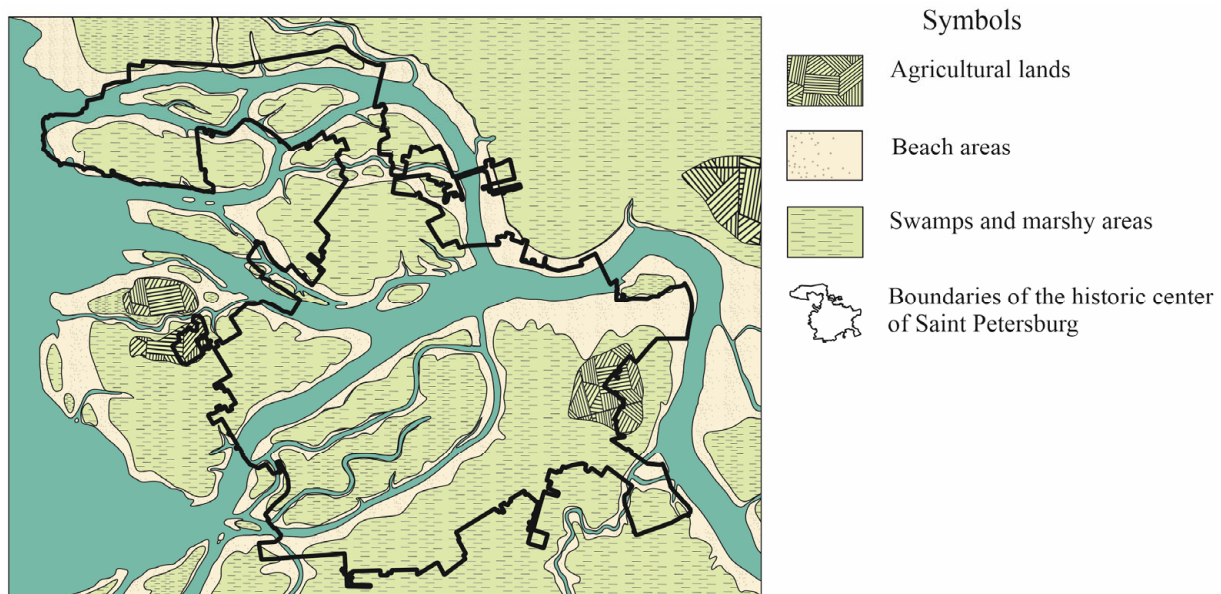
Tectonic faults allow the location and direction of the palaeovalleys of the Pra-Neva system to be traced, which are filled with Quaternary sandy-clay sediments of considerable thickness. From engineering-geological perspectives, these soils represent relatively weak water- and water–gas-saturated formations (see Figure 1) [16–19]. Palaeovalley zones are characterized by complex engineering-geological, geotechnical, and geoenvironmental conditions, as they are considered drainage depressions, including those for contaminated underground water. Figure 1 illustrates that approximately 50% of the historical center of St. Petersburg's total area is located within palaeovalley development zones.

It is pertinent to note that within the zone of the deepest palaeostructure, which runs along the left bank of the Neva River, there is a concentration of architectural and historical monuments of world significance—the complex of Winter Palace buildings, the General Staff, the Admiralty, and Saint Isaac's Cathedral is situated within the slope section of the palaeovalley.

Outside the palaeovalleys, there is an improvement in engineering-geological and geotechnical conditions due to a decrease in the thickness of weak Quaternary deposits, as the Upper Kotlin clays of the Upper Vendian lie at a depth of 25 m or less [16].

The regional formation of swamps and their long-term existence influenced the features of the underground space components in the historical center of Saint Petersburg, which is located in the island (delta) part of the city and is characterized by the lowest absolute elevations.

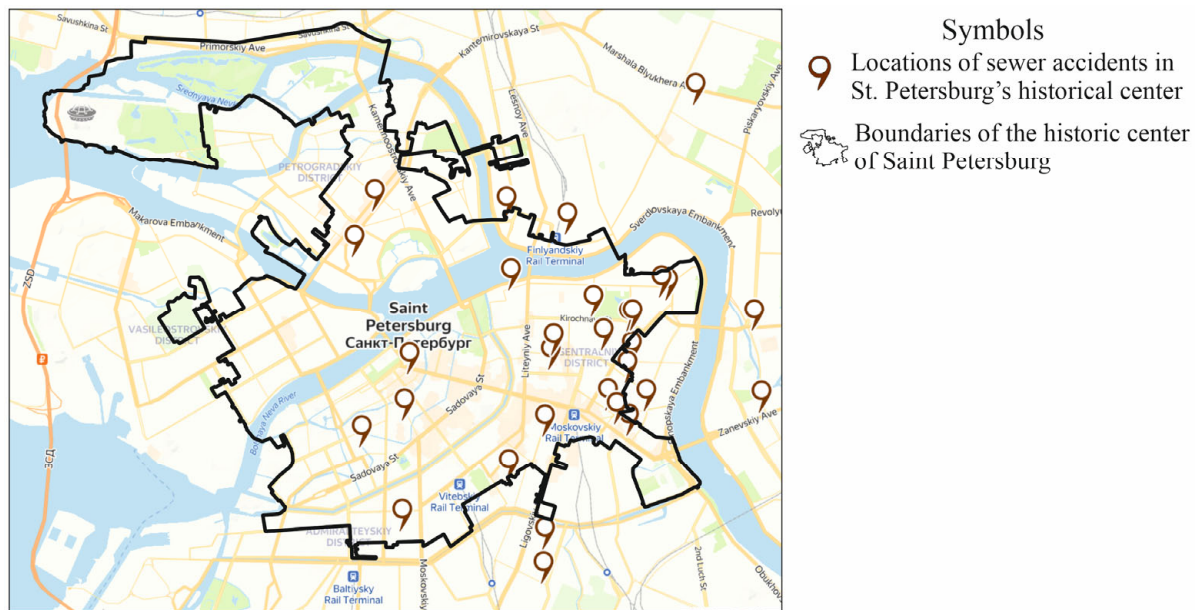
The widespread swamping of the territory in pre-Petrine times is confirmed by Swedish cartographic materials created at the end of the 17th century and beginning of the 18th century (Figure 2).



**Figure 2.** A map of the area from 1698 indicating territories occupied by swamps (constructed on the basis of a Swedish map from the archives of the Cartographic Department of the Saint Petersburg Public Library).

According to the results of multi-year research conducted by Professor R.E. Dashko at the Department of Hydrogeology and Engineering Geology of Empress Catherine II Saint Petersburg Mining University, it has been established that the long-term existence of swamps in various regions has a negative and irreversible impact on the formation and changes in engineering-geological, geotechnical, and geoenvironmental conditions [20]. Swamps serve as a natural source of microorganisms of various physiological groups and gases, as well as contribute to the transformation of physical–chemical and biochemical conditions in underground space due to the enrichment of the underlying sandy-clay water-saturated soils with organic compounds of abiotic and biotic origin to a depth of 30 m and more [20]. During the engineering preparation of the territory as the megapolis developed, swamp sediments up to 2–3 m thick were entirely eliminated, while thicker deposits were only partially eliminated and overlain by technogenic formations. The negative impact of buried peat on underlying soil and aquifers persists to this day.

The regional contamination source in the underground space is household wastewater, whose removal system either did not exist (18–19th centuries) or had design imperfections (20–21st centuries). The first regional water disposal system in Leningrad was put into service only in 1935 on Vasilyevsky Island. The current state of the sewerage systems in the city's historical center can be seen from the scheme shown in Figure 3 [21].



**Figure 3.** Locations of sewer accidents in the historical part of Saint Petersburg in 2022–2023 [21].

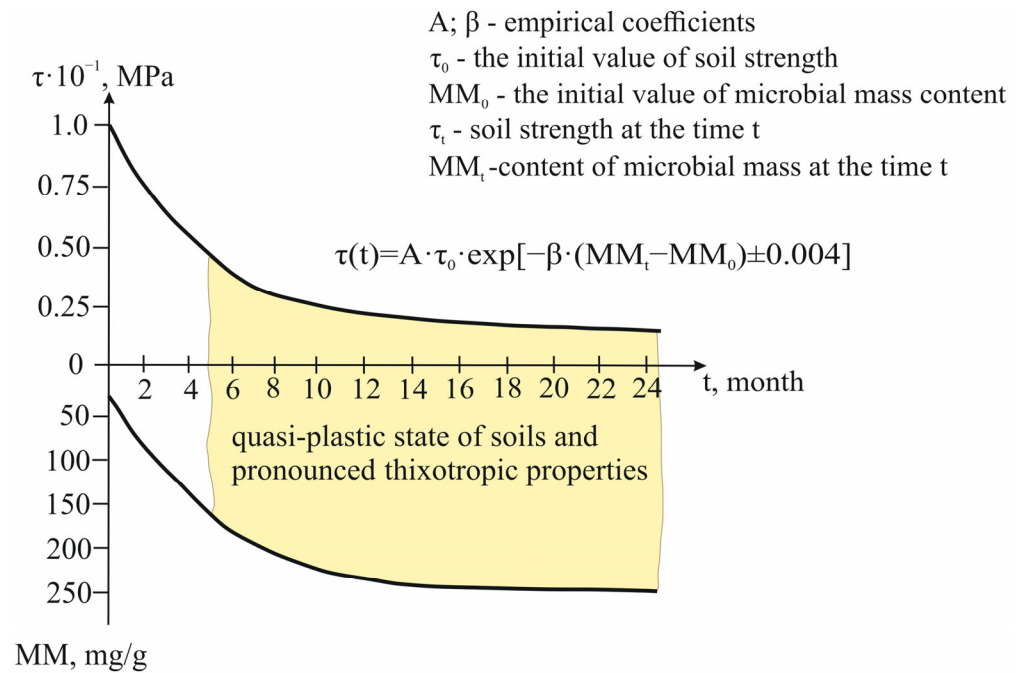
Sewers are characterized by the presence of organic materials such as proteins, fats, carbohydrates, inorganic compounds of sulfur, nitrogen, phosphorus, etc., as well as microorganisms, the content of which is  $10^7$ – $10^8$  CFU (colony-forming units) in 1 mL of sewage effluent [20,22,23]. The microbiota introduced by leaks from water disposal systems increases the number and diversity of existing indigenous (swamp) forms in underground space, which accelerates and deepens the negative changes in sandy-clay soils and the transformation of underground water composition and promotes the development of dangerous natural–technogenic processes such as biochemical gas formation and biocorrosion of building materials [20,24].

Notably, the presence of hydrotroilite ( $\text{FeS} \cdot n\text{H}_2\text{O}$ ) in the sandy-clay strata below the groundwater level in the historical center indicates microbial activity and specific physicochemical conditions of the underground space, suggesting a reducing environment ( $\text{Fe}^{2+}$ ) and the presence of hydrogen sulfide ( $\text{H}_2\text{S}$ ) as a product of sulfate-reducing bacteria's life activity, which are usually found in rich microbiocenoses [20].

The formation of technogenic formations (in terms of thickness, composition, and age) is inextricably linked to the engineering preparation of the city's territory as it developed: by removing swamps, raising the ground surface level with the construction of river and canal embankments, moving the shoreline, and eliminating reservoirs and streams. The neglect of eliminated water bodies (18–20th centuries) in the megapolis leads to emergencies, often related to architectural and historical monuments. The long-term development of deformation in the western part of the Yusupov Palace on the Moyka River is associated with the presence of a filled-in canal in its foundation, which connected the abovementioned river with the Krivusha River (Griboyedov Canal) in the period of 1758–1764.

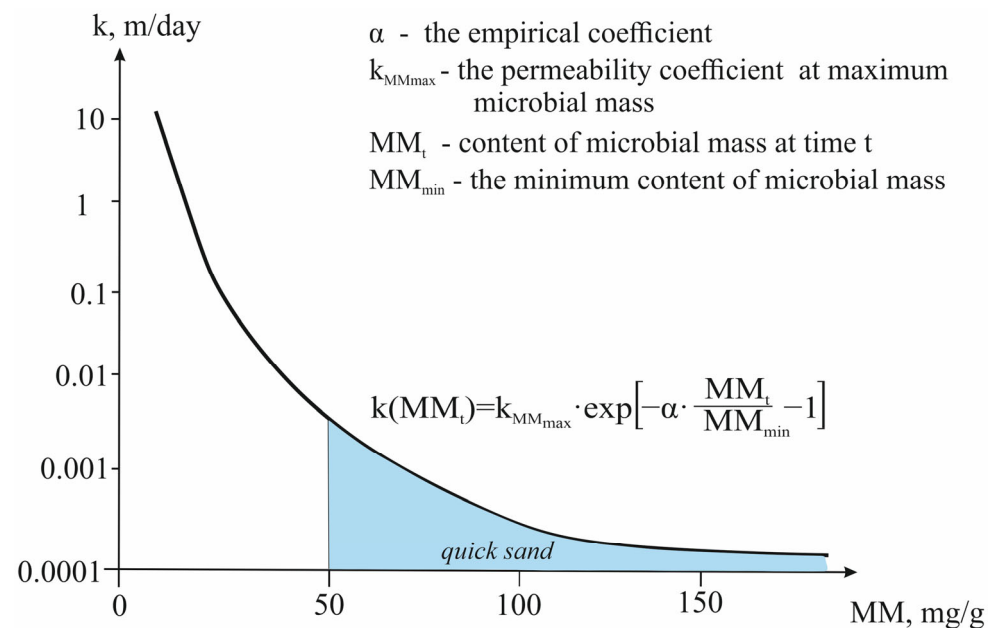
Moreover, in New York, construction companies widely use a map of filled-in watercourses and swamps, created in 1865 by the topographer E.L. Viele, to minimize the risks of emergencies at construction sites [25].

The regional impact of swamps and water disposal systems' leaks has an irreversible and negative effect on the underlying Quaternary soils. Their enrichment by microorganisms and abiotic organics leads to the formation of biofilms on mineral particles, reducing the angle of internal friction  $\varphi$  and contributing to the transition of sands into quick sand and clay soils into a quasi-plastic state (Figure 4) [17,20,26].



**Figure 4.** Decrease in the clay soil strength ( $\tau$ ) over time ( $t$ ) as the microbial mass ( $MM$ ) increases [20].

According to the results of experimental studies, fine- and medium-grained sands with a microbial mass content of more than 50 mg/g of dry rock, determined by the method of M. Bradford, have a permeability coefficient  $k$  of up to  $10^{-3}$  m/day or less (Figure 5) [20].



**Figure 5.** Decrease in the permeability coefficient ( $k$ ) of water-saturated fine- and medium-grade sands as the microbial mass ( $MM$ ) increases [20].

It should be noted that the Quaternary deposit layer in the historical center of Saint Petersburg is represented by lake-marine, lake-glacial, and moraine soils.

The confined Lower Kotlin aquifer and the unconfined groundwater aquifer have regional developments in Saint Petersburg. Groundwater is characterized by significant contamination due to leakage from non-pressure water disposal systems, which leads to a decrease in the oxidation–reduction potential  $Eh$  to negative values of less than  $-100$  mV.

An increased content of organic compounds, as well as nitrogen, sulfur, phosphorus, chlorides, potassium, and sodium, characteristic of sewers, is observed [27]. The interpretation of the abnormally high amount of alkali and alkaline earth elements is based on their leaching process from the masonry of foundations and binders, as well as from the walls of basements. These groundwater results were obtained from in situ studies in the city's monitoring network wells in the 20–21st centuries.

The impact of the confined Lower Kotlin aquifer (with pressures exceeding 100 m) should be analyzed in palaeovalley zones with large thicknesses of the active zone of heavy architectural and historical monuments (e.g., Saint Isaac's Cathedral). This aquifer can affect the stress–strain state of foundation soils and contribute to the destruction of foundations due to various types of corrosion caused by the physical, chemical, and biochemical activity of its water [16,17,20].

### 3.2. Results of Underground Space Research at the Local Level

Among the natural factors at this level of underground space in St. Petersburg's historical center, it is necessary to pay attention to the development of the confined Moscow–Ostashkov intermoraine aquifer, which is associated with palaeovalley zones. This aquifer is often not considered when developing restoration or reconstruction projects for cultural heritage objects. The presence of water pressures of 30 m or more requires consideration when carrying out studies related to the restoration of the underground part of architectural and historical monuments, particularly the deepening of basements. The chemical composition and biochemical characteristics of this aquifer require an analysis of the possibility of hardening bored pile concrete and other underground structures.

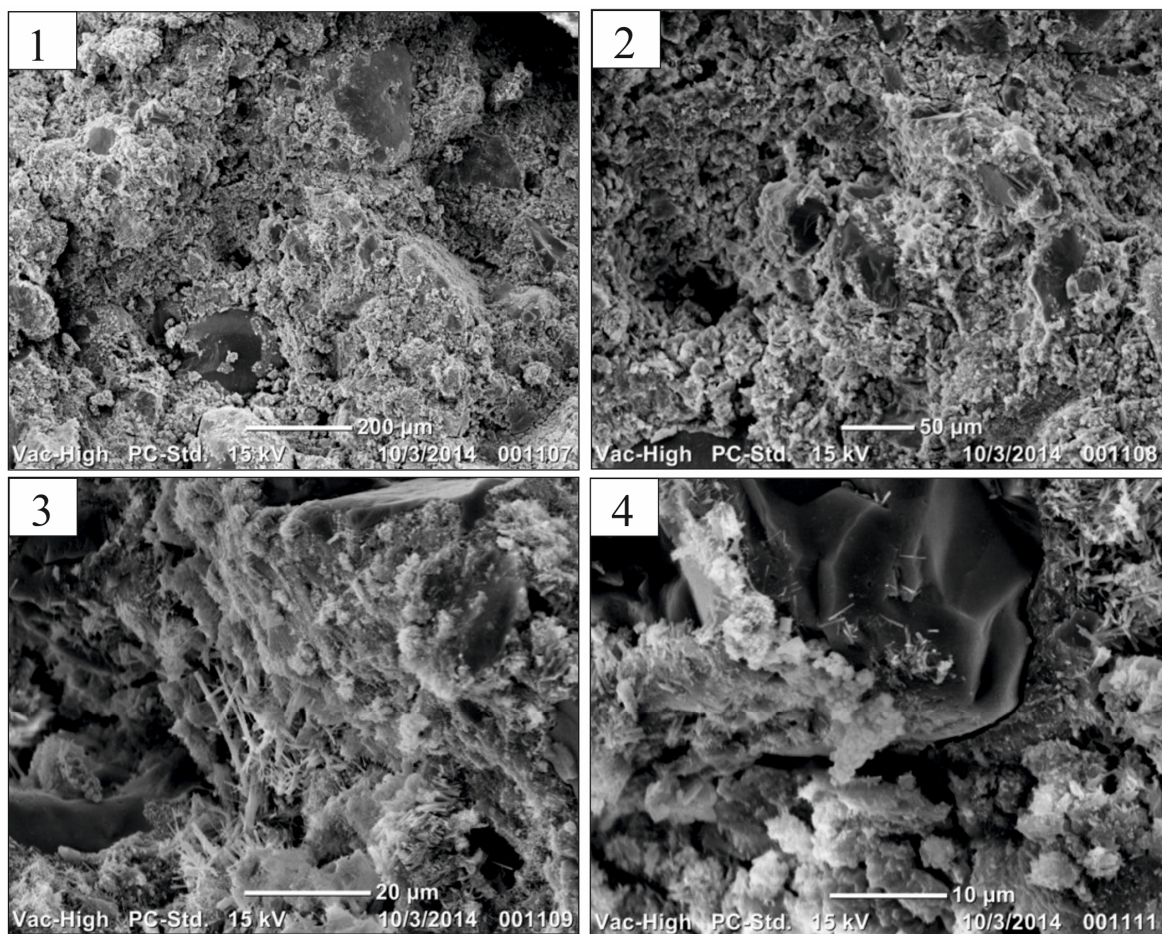
Sampling of underground water in the area of the “Plushchad Alexandra Nevskogo I” metro station to investigate the causes of the destruction of the escalator lining materials, which crossed the mentioned aquifer, showed that the greatest destruction of the bearing lining was recorded precisely in the zone of contact with the intermoraine aquifer (Table 1) [20].

**Table 1.** Chemical composition of the Moscow–Ostashkov intermoraine aquifer (in the area of the “Plushchad Alexandra Nevskogo I” metro station) (according to data from the JSC “Hydroproject”).

| Analysis Elements             | Element Content, mg/dm <sup>3</sup> |
|-------------------------------|-------------------------------------|
| Ca <sup>2+</sup>              | 53.0                                |
| Mg <sup>2+</sup>              | 21.0                                |
| Na + K                        | 378.0                               |
| SO <sub>4</sub> <sup>2−</sup> | 123.0                               |
| Cl <sup>−</sup>               | 420.0                               |
| HCO <sub>3</sub> <sup>−</sup> | 488.0                               |
| Mineralization                | 1344.0                              |

The destruction of reinforced concrete was also noted, and the number of bacteria at this depth reached a maximum of 3900 CFU per 1 g. Among the micromycetes, separate species with highly destructive properties were isolated: *Aspergillus niger*, *Cladosporium sphaerospermum*, *Penicillium lanosum*, and *Trichoderma viride*. Due to the formation of biofilms of complex microbial communities on the surface of concrete structures, the degradation of cement minerals—aluminates and calcium silicates—is observed as a result of the selective extraction of necessary elements by microorganisms. The surface destruction is clearly visible when the samples are examined by scanning electron microscopy (Figure 6).

Contamination and transformation of the underground space components in St. Petersburg's historical center occurred locally, primarily affecting Quaternary sandy-clay soils and groundwater. This happened in areas where ancient settlements existed before the city's founding and during the Petrine and post-Petrine periods due to the functioning of cemeteries and markets.



**Figure 6.** The surface condition of corroded concrete as observed using scanning electron microscopy at various scales: (1)—concrete surface (200  $\mu\text{m}$ ); (2)—degradation of the protective carbonate layer of concrete (50  $\mu\text{m}$ ); (3)—needle-like minerals of newly formed minerals (20  $\mu\text{m}$ ); (4)—needle-like crystals and spherical structures in concrete (10  $\mu\text{m}$ ) (photos taken by D.Yu. Vlasov, 2014).

In the 18–19th centuries, at least 10 historical center cemeteries were eliminated, and the surviving ones have significantly decreased in size [28]. Groundwater is impacted irreversibly by cemeteries due to the significant increase in organic substances, mainly proteins, which directly results in an increase in the indicator of chemical oxygen demand (COD), which is known to determine the overall content of both easily soluble and hardly soluble organics. Additionally, there is a notable increase in the amount of ammonium ( $\text{NH}_4^+$ ), as well as alkaline earth elements such as calcium  $\text{Ca}^{2+}$  and magnesium  $\text{Mg}^{2+}$  (Table 2) [20].

Ground water has high levels of soluble organic compounds, affecting its oxidation–reduction and acid–alkali conditions. The discrepancies in the chemical composition of groundwater are explained by the fact that Hare Island, where Commandant’s cemetery is located, has a small area (0.55  $\text{km}^2$ ) and is consequently characterized by a flushing regime due to the influence of the Neva River and Kronverk Canal.

Local sources of contamination of the underground space of the historical center were primarily markets for the sale of large and small cattle and horses, which served as sources of organic and inorganic compounds entering the underground space. Their impact on the chemical composition of groundwater is still observed even after the closure of such markets. Such waters present a highly aggressive environment for the building materials of underground structures (Table 3).

**Table 2.** Fragment of groundwater composition under the influence of ancient cemeteries (according to the research of Professor R.E. Dashko).

| Analysis Elements                                                 | Element Content, mg/dm <sup>3</sup> |                                                        |                                                                                       |
|-------------------------------------------------------------------|-------------------------------------|--------------------------------------------------------|---------------------------------------------------------------------------------------|
|                                                                   | Alexander Nevsky Lavra              | Commandant's Cemetery in the Petropavlovskaya Fortress | * Park Zone (Beyond Zones of Technogenic Contamination of the Subsurface Environment) |
| Ca <sup>2+</sup>                                                  | 150.0                               | 100.0                                                  | 4.0–41.0                                                                              |
| Mg <sup>2+</sup>                                                  | 116.4                               | 66.0                                                   | 5.0–17.0                                                                              |
| Na + K                                                            | 7.09                                | 1.89                                                   | 2.5–66.0                                                                              |
| NH <sub>4</sub> <sup>+</sup>                                      | 123.0                               | 2.9                                                    | 1.2–3.7                                                                               |
| SO <sub>4</sub> <sup>2−</sup>                                     | 176.0                               | 2.0                                                    | 18.0–80.0                                                                             |
| Cl <sup>−</sup>                                                   | 40.0                                | 30.0                                                   | 5.0–28.0                                                                              |
| HCO <sub>3</sub> <sup>−</sup>                                     | 1189.5                              | 396.5                                                  | 79.0–189.0                                                                            |
| NO <sub>3</sub> <sup>−</sup>                                      | 1.2                                 | 0.9                                                    | 1.1–7.5                                                                               |
| Mineralization                                                    | 1804.6                              | 604.1                                                  | 170.0–285.0                                                                           |
| CO <sub>2</sub> (aggressive)                                      | 59.4                                | 19.8                                                   | 132.0–190.0                                                                           |
| PO <sup>1</sup> , mgO <sub>2</sub> /dm <sup>3</sup>               | 35.2                                | 16.0                                                   | 6.0–30.0                                                                              |
| COD <sup>2</sup> , mgO <sub>2</sub> /dm <sup>3</sup>              | 310.4                               | 46.6                                                   | Was not determined                                                                    |
| BOD <sub>5</sub> <sup>3</sup> , mgO <sub>2</sub> /dm <sup>3</sup> | 27.2                                | 2.8                                                    | 1.5–6.0                                                                               |
| pH (in situ)                                                      | 6.9                                 | 7.4                                                    | 5.3–6.8                                                                               |
| Eh, mV (in situ)                                                  | −108.0                              | −12.5                                                  | Was not determined                                                                    |

<sup>1</sup> Permanganate oxidation; <sup>2</sup> chemical oxygen demand; <sup>3</sup> biological oxygen demand in 5 days; \* The park area experiences an increase in bog formation, which causes an increase in the content of organic compounds.

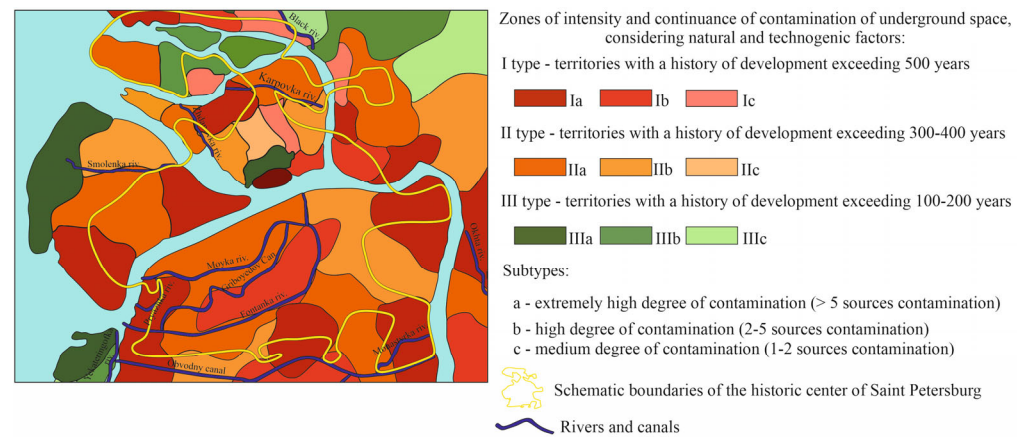
**Table 3.** The chemical composition of groundwater fragments in areas of long-term market influence (\* according to the GRII Trust data; \*\* according to the research of Professor R.E. Dashko; \*\*\* according to the research of Professor R.E. Dashko).

| Analysis Elements                                   | Element Content, mg/dm <sup>3</sup>   |                                                                                          |                                                                                         |
|-----------------------------------------------------|---------------------------------------|------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
|                                                     | * Apraksin Dvor (Operated 1754–1860s) | ** Formerly Horse Market, Operated for over 180 Years Until the End of the 19th Century) | *** Park Zone (Beyond Zones of Technogenic Contamination of the Subsurface Environment) |
| Ca <sup>2+</sup>                                    | 128.0–169.0                           | 132.0                                                                                    | 4.0–41.0                                                                                |
| Mg <sup>2+</sup>                                    | 37.7–158.0                            | 108.2                                                                                    | 5.0–17.0                                                                                |
| Na + K                                              | 51.1–170.0                            | 442.1                                                                                    | 2.5–66.0                                                                                |
| NH <sub>4</sub> <sup>+</sup>                        | 0.6–4.0                               | -                                                                                        | 1.2–3.7                                                                                 |
| SO <sub>4</sub> <sup>2−</sup>                       | 81.5–240.0                            | 110.2                                                                                    | 18.0–80.0                                                                               |
| Cl <sup>−</sup>                                     | 80.0–156.0                            | 451.6                                                                                    | 5.0–28.0                                                                                |
| HCO <sub>3</sub> <sup>−</sup>                       | 466.7–1135.0                          | 1232.2                                                                                   | 79.0–189.0                                                                              |
| NO <sub>3</sub> <sup>−</sup>                        | 0.2–24.0                              | 8.1                                                                                      | 1.1–7.5                                                                                 |
| Mineralization                                      | 854.1–2043.3                          | 2500.0                                                                                   | 170.0–285.0                                                                             |
| CO <sub>2</sub> (aggressive)                        | 16.5                                  | -                                                                                        | 0.0–33.0                                                                                |
| PO <sup>1</sup> , mgO <sub>2</sub> /dm <sup>3</sup> | 27.0–32.0                             | 36.8                                                                                     | 6.0–30.0                                                                                |
| pH                                                  | 7.5                                   | 7.0                                                                                      | 5.3–6.8                                                                                 |
| Eh, mV (in situ)                                    | Was not determined                    | −127.0                                                                                   | Was not determined                                                                      |

<sup>1</sup> Permanganate oxidation; \*\*\* The park area experiences an increase in bog formation, which causes an increase in the content of organic compounds.

Based on the results of comprehensive studies and archival materials, a schematic map was created for Saint Petersburg, reflecting the degree and duration of contamination in its individual territories (Figure 7).

Figure 7 shows that the longest transformation of underground space occurred in the historical city center, which should be considered when conducting studies at the object level. Notably, the territories with the longest development term have the highest number of accidents during the construction and reconstruction of structures with deep underground space development (up to 28 m).



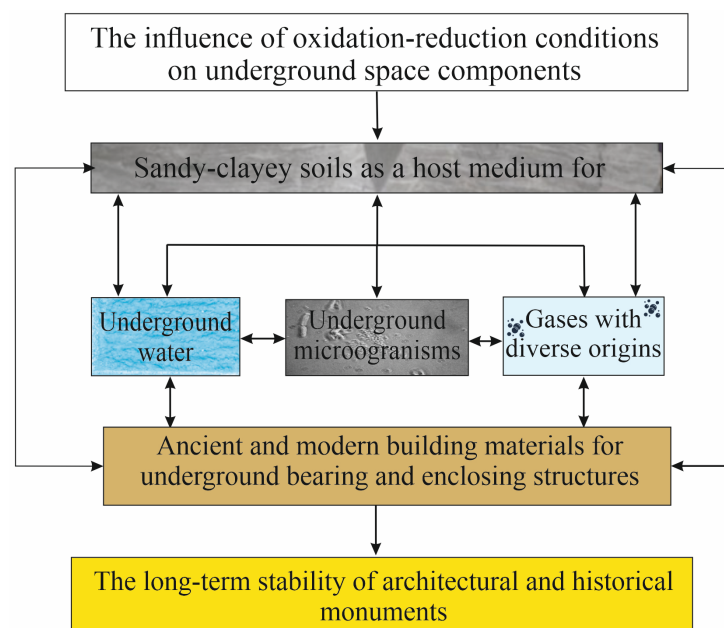
**Figure 7.** Schematic map of St. Petersburg's historical center of underground space contamination intensity and duration (compiled by V.A. Gorskaya and R.E. Dashko) [29].

#### 4. Discussion

##### 4.1. Discussion of Engineering-Geological and Geotechnical Research Results on Underground Space at the Object Level

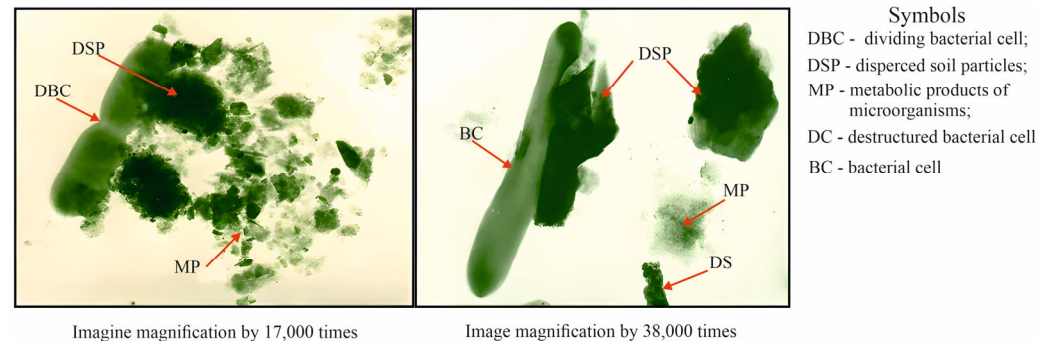
When developing restoration or reconstruction projects for architectural and historical monuments based on completed engineering-geological and geotechnical research, it is necessary to consider natural factors and technogenic transformations of underground space components at both the regional and local levels, as previously mentioned.

Engineering-geological and geotechnical research at the object level should begin with an assessment of the oxidation–reduction conditions in the underground space of the object, which predetermine the state and the physicochemical properties of soils, physicochemical, chemical, and biochemical characteristics of underground water, and the development of microorganism taxa in relation to oxygen: anaerobic, facultative, and aerobic. The activity of physiological groups of microbiota allows for the prediction of the generation of various biochemical gases. The state of the underground space component, depending on oxidation–reduction conditions, determines the corrosivity of the containment medium towards ancient and modern underground structural materials (Figure 8).



**Figure 8.** Block diagram of the interaction between oxidation–reduction conditions and underground space components (compiled by the authors).

Under reducing conditions, clayey soils lack rigid cementation bonds due to the reduction of trivalent iron  $\text{Fe}^{3+}$  compounds and predominantly exhibit molecular bonds. When biofilms form on solid particles, these soils are characterized as quasi-plastic mediums due to their deformation behavior, as previously mentioned (Figure 9).



**Figure 9.** Examples of interactions between bacterial cells and clay particles obtained via polarization electron microscopy (from the archives of Professor R.E. Dashko).

The physicochemical, chemical, and biochemical characteristics of underground water are closely related to the activity of microorganisms, for which water serves as one of the main sources of nutrients and energy substrates. During the downward infiltration of underground water, microbiota transport and colonization of deeper soil horizons occur, and in the presence of high water pressure in interstratal water and their upward migration, the overlying impermeable layers and aquifers are affected. Under anaerobic conditions, nitrogen compounds are fixed in the form of  $\text{NH}_4^+$ , which has an organic or inorganic origin; sulfur compounds in the form of the highly soluble biochemically generated gas  $\text{H}_2\text{S}$ ; and iron compounds in the form of  $\text{Fe}^{2+}$ .

During metabolism, all microorganisms generate  $\text{CO}_2$ , which is soluble in water. Microbiological research in the underground space of St. Petersburg's historical center determined the main heterotrophic microorganism taxa that are divisible into those generating gases while utilizing organic matter and those lacking this ability. It is necessary to consider the solubility of gases in water and their aggressiveness towards construction materials. The generation of sparingly soluble gases, such as molecular nitrogen  $\text{N}_2$  (denitrifying bacteria), molecular hydrogen  $\text{H}_2$  (hydrogen-generating bacteria), and, much less frequently, methane  $\text{CH}_4$  (usually observed in zones of buried peats with low Eh values and high organic compound content), should be considered from two perspectives. The deposition of sparingly soluble gases is accompanied by an increase in gas-dynamic pressure and, as a result, a change in the stress-strain state of the soil layer. During their dissipation, water-saturated soils transition to a water-gas-saturated state and decompress [15]. Microscopic bubbles of sparingly soluble gases in soil pores, considered solid (incompressible) in gas dynamics due to high surface tension, act as ball bearings according to Laplace's law. This results in a decrease in the angle of internal friction  $\varphi$  and pore pressure to zero values at a saturation ratio  $S_r$  of 0.95 or less [30,31].

Particular attention should also be paid to the exhalation of deep gas, radon, which is recorded in fracture zones. In these zones, radiation leads to an increase in microbial activity and population growth, as proven by special research initiated in the first half of the 20th century and continuing to the present day [32,33].

A reducing environment and anaerobic microorganism activity have a destructive effect on underground bearing and enclosing structures due to biocorrosion processes, which are practically not studied during engineering-geological and geotechnical research. In Russian engineering survey practice, only four types of corrosion are investigated—acidic, carbon dioxide, sulfate, and magnesia—which is insufficient for predicting the nature and activity of building material destruction in the multi-component underground space.

Biocorrosion usually occurs due to underground microorganisms' activity that form bacterial mats on building material surfaces and extract elements necessary for cell life from material crystal lattices. Additionally, material destruction is observed due to microbial metabolism products such as proteins, organic and inorganic acids, and gases with various solubilities, such as  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ , and  $\text{H}_2$  [34,35] (Figure 10).



**Figure 10.** Deep corrosion damage of metal underground structures in the restored basement of an old residential building in Saint Petersburg (photo by I.V. Alekseev, 2016) [36].

Enzyme action on construction surfaces can generate complex compounds. Iron-reducing bacteria contribute to the removal of reduced  $\text{Fe}^{2+}$  from steel structures, reducing their density and strength.

The formation of organic and inorganic acids by underground microorganisms contributes to a decrease in the pH of the aqueous environment to 3–4 and below, in which building materials such as carbonate rocks used as foundations of old buildings and binders are unstable [20,37]. Their destruction is indicated by the chemical composition of the groundwater, which is enriched with the alkaline earth elements  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ .

Moreover, in an acidic environment, the active destruction of steel structures occurs. During  $\text{H}_2\text{S}$  dissociation in water according to the  $\text{H}_2\text{S} \leftrightarrow \text{H}^+ + \text{HS}^-$  scheme, the accumulation of  $\text{H}^+$  ions on the metal surface leads to their diffusion into the crystal lattice of the metal with the subsequent formation of the metal hydride  $\text{Me}_m\text{H}_n$ . The formation of metal hydrides causes an increase in the volume and decompaction of the near-surface structure, which in turn accelerates the diffusion process and deepens the zone of destruction. The sparingly soluble gas  $\text{H}_2$ , due to its diffusion into metals, exerts similar effects. This process is called hydrogen embrittlement, which leads to premature failure of the pipeline, reinforced concrete armature, steel beams, and other structures.

#### 4.2. Recommendations for Conducting Field and Laboratory Research in the Foundation Zone of Cultural Heritage Objects

Engineering-geological and geotechnical field research must examine soils in the foundation zone of historical buildings to understand changes in their condition due to the weight of long-standing cultural heritage objects, which may increase during restoration or reconstruction, especially when recreating structures. In the theory of soil mechanics and in structural stability calculation practice, it is considered that water-saturated clay soils under long-term pressure from a structure increase their strength due to filtration consolidation [38,39]. However, observations of functioning objects have shown that often in the foundation zone, the physical state of the soils remains stable, and in some instances, their reconsolidation may occur due to gas formation and increased hydrophilicity [17]. In some cases, weak soils are squeezed out from under the foundation [40,41].

The most reliable results on the composition, state, and physicommechanical properties of soils in the foundation of cultural heritage objects can be obtained by core drilling in cellars with sufficient height for safe rig operation. Soil sampling should be carried out over the entire depth of the foundation zone. A comparative assessment of the density, moisture,

consistency, and shear strength of soils according to the unconsolidated-undrained scheme under triaxial compression conditions should be performed for soils of the same genesis and composition sampled in the foundation zone of the structure and near its contour [38].

The study of underground water in the foundation area of an architectural and historical monument should be carried out according to an expanded list of indicators, including mandatory investigations of both hard-to-oxidize and easily oxidizable organic compounds: their total COD content, the amount of easily oxidizable organic matter (permanganate oxidation), and the biological indicator BOD to determine aerobic microorganisms. In addition, it is necessary to determine silicic acid, a marker of the destruction of silicate geomaterials. The wide use of selective electrodes is recommended, especially for defining the content of unstable compounds and variable-valence elements in underground water. The gas component of the underground space is only investigated under field conditions to predict the stress–strain state of the soil layer and the corrosion of building materials. Unfortunately, selective electrodes have not found wide application in Russian engineering-geological and geotechnical research in cities and mining regions.

Soil, underground water, and damaged building material samples should be analyzed via metagenomic analysis and cultivation on nutrient media while preserving *in vitro* pH and redox conditions to obtain information about the microbial community. These studies should form the basis for identifying the causes of building material corrosion and selecting materials that are stable in aggressive environments for restoring or reconstructing the underground part of cultural heritage objects and creating waterproofing for basement walls and foundations.

#### *4.3. Some Examples of the Methodology's Application in Saint Petersburg and Abroad*

The analysis of the underground space of Saint Petersburg as a multi-component system started to be implemented in the theory and practice of preserving architectural and historical monuments as early as the late 20th century during the study of the complex of the New Hermitage buildings. Studies of the causes of foundation destruction in the New Hermitage made it possible to establish high microbial contamination of soils and groundwater. Biocorrosion processes led to the complete destruction of wooden bed timbers, limestone slabs, and brickwork of strip foundations, especially in areas of active groundwater contamination due to leaks from sewage systems [42].

For the past 25 years, research has been conducted on the causes of the long-term settlement and southwestward tilt of Saint Isaac's Cathedral in the absence of filtration consolidation and with the development of soil heave in the western direction [43].

During the investigation of the Old Saint Petersburg Stock Exchange, the destruction of its foundations due to biocorrosion processes was discovered. Experimental studies of anaerobic sulfate-reducing bacteria revealed their significant role in transforming the components of the underground space, particularly in the biocorrosion of ancient building materials.

As part of the study to ensure the long-term stability of the Yusupov Palace on the Moyka River, specialized studies were conducted to determine the causes of the creep deformation in the western part of the palace. The foundations of this part were found to be located within a filled-in canal, which was only discovered during our investigations and was previously unknown to specialists. This finding largely determined the technology used for the repair work in the corresponding palace rooms.

In recent years, the authors have been studying the current state of the above-ground and underground elements of the Alexander Column—the central dominant feature of Palace Square in Saint Petersburg. The authors were the first to draw specialists' attention to the development of the column's tilt and the causes behind it. Additionally, significant attention has been given to the nature of the cracks in the monolithic granite fust of the monument, with their formation linked to the structural and tectonic conditions of the region where the material was quarried [44].

Given the particularly complex engineering-geological, geotechnical, and geo-environmental conditions of St. Petersburg's historical center, it is necessary to organize and conduct comprehensive monitoring of cultural heritage objects after completing restoration or reconstruction work. This should include geodetic observations of the dynamics of deformation development and its progression [45,46], geophysical methods for studying the condition of object elements [47], as well as original and non-standard research on underground space component changes according to the presented block diagram (see Figure 8). Recommendations for organizing and conducting comprehensive monitoring via modern methods based on the multi-component nature of the underground space have been developed for several restored and reconstructed 19th-century churches, as well as for the aforementioned architectural and historical monuments [43,44].

The approach to studying the underground space as a multi-component system is used not only for cultural heritage objects located in Saint Petersburg but also for developing comprehensive monitoring of the conditions of some architectural and historical monuments in one of the world's oldest cities—Hanoi (Socialist Republic of Vietnam), which has existed for more than 1000 years. The analysis of the causes of destruction of the Hanoi Cathedral (second half of the 19th century), the Hanoi Flag Tower (first half of the 19th century), and the Doanmon Gate of the Imperial Citadel of Thang Long (15th century) is reflected in a published study and in the thesis for the degree of Ph.D. by Nguyen Tien Chung titled "Engineering-Geological Monitoring of the Underground Space in the Historical Center of Hanoi (the Socialist Republic of Vietnam)" led by Professor R.E. Dashko [48].

The concept of a multi-component underground space is strongly recommended for application in historical megapolises with concentrated cultural heritage objects. These areas often feature geological sections containing buried bogs and sandy-clay soils with organic matter. Moreover, long-term anthropogenic contamination of soils and underground water has been reported over the centuries. Cities with such conditions include London, Cologne, Venice, Mexico City, Santa Fe de Bogota, Washington, and others. For example, the causes of the Leaning Tower of Pisa's tilt are linked to its location in the Arno River valley and the presence of alluvial soils containing organic compounds in the foundation zone of the tower's southern part. This is not considered a factor determining the development of the tilt. Using the principles of multi-component underground space can help enhance technologies to ensure the stability of this unique monument.

The approach of the underground space as a multi-component system during its development and use has been successfully employed and continues to be used by one of the authors of this article to enhance the safety of mining operations and underground methods of mining [49–51].

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## References

1. Viggiani, C. Cultural heritage and geotechnical engineering: An introduction. In Proceedings of the 2nd International Symposium on Geotechnical Engineering for the Preservation of Monuments and Historic Sites, Napoli, Italy, 30–31 May 2013; p. 12.
2. Burland, J.B.; Jamiolkowski, M.B.; Squeglia, N.; Viggiani, C. *The Tower of Pisa: History, Construction and Geotechnical Stabilization*; CRC Press: London, UK, 2020; p. 62. [CrossRef]

3. Hemeda, S.; Sonbol, A. Sustainability problems of the Giza pyramids. *Herit. Sci.* **2020**, *8*, 8. [CrossRef]
4. Hemeda, S. PLAXIS 3D numerical analysis of complex geotechnical problems of colossal built heritage. *Herit. Sci.* **2024**, *12*, 32. [CrossRef]
5. Coli, M.; Iwasaki, Y. Novel approaches and technologies for heritage buildings conservation: Editorial. *Appl. Sci.* **2021**, *11*, 10597. [CrossRef]
6. Iwasaki, Y.; Fukuda, M.; Ishizuka, M.; McCarthy, R.; Akazawa, Y.; Nakagawa, T.; Ly, V. The authenticity and the integrity of the soil and the foundation of heritage structure of Bayon Temple, Angkor. In *Geotechnical Engineering for the Preservation of Monuments and Historic Sites III*; Lancellotta, R., Viggiani, C., Flora, A., de Silva, F., Mele, L., Eds.; CRC Press: London, UK, 2022; pp. 325–336. [CrossRef]
7. Nikitin, N.P. *Auguste Montferrand: Design and Construction of Saint Isaac's Cathedral and the Alexander Column*; Leningradskoe otdelenie Soyuz Sovetskikh Arhitektorov: Saint Petersburg, Russia, 1939; p. 348. (In Russian)
8. Shashkin, A.G.; Shashkin, V.A. Is it possible to preserve historical monuments on the basis of standards for new construction? *Geotechnics* **2021**, *13*, 20–30. (In Russian) [CrossRef]
9. Shashkin, A.G.; Shashkin, V.A.; Bogov, S.G.; Voronov, A.S. Waterproofing of architectural monuments. *Geotechnics* **2022**, *14*, 28–41. (In Russian) [CrossRef]
10. Ulitsky, V.M.; Shashkin, A.G. Preservation of architectural monuments and provision of their mechanical safety. *Ind. Civ. Eng.* **2017**, *7*, 31–39. (In Russian)
11. Sotnikov, S.N. The settlement of Saint Isaac's Cathedral in Leningrad. In *Foundation Construction in Conditions of Weak and Frozen Soils: Inter-University Thematic Collection of Papers*; Dalmatov, B.I., Ed.; LISI [Leningrad Civil Engineering Institute]: Saint Petersburg, Russia, 1986; pp. 7–18. (In Russian)
12. Mangushev, R.A.; Osokin, A.I.; Sotnikov, S.N. *Geotechnics of St. Petersburg. Experience in Construction on Weak Soils*; ACB: Moscow, Russia, 2018; p. 386. (In Russian)
13. Pashkin, E.M. *Engineering-Geological Diagnostics of Deformations of Architectural Monuments*; ANO «Tradiciya»: Moscow, Russia, 2022; p. 368. (In Russian)
14. Pashkin, E.M. Lift and moving of architectural monuments as the main methods of their preservation. *Geotechnics* **2022**, *14*, 18–26. (In Russian) [CrossRef]
15. Protosenya, A.G.; Alekseev, A.V.; Verbilo, P.E. Prediction of the stress-strain state and stability of tunnel face at the intersection of disturbed zones of the soil mass. *J. Min. Inst.* **2022**, *254*, 252–260. [CrossRef]
16. 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. *J. Min. Inst.* **2022**, *254*, 180–190. [CrossRef]
17. Dashko, R.E. *Engineering-Geological Analysis and Assessment of Water-Saturated Clayey Rocks as Foundation for Structures*; Publishing house of the Institute “Georekonstrukciya”: Saint Petersburg, Russia, 2015; p. 384. (In Russian)
18. Dashko, R.E.; Aleksandrova, O.Y.; Kotukov, P.V.; Shidlovskaya, A.V. Special aspects of geotechnical conditions of St. Petersburg. *Urban. Dev. Geotech. Constr.* **2011**, *1*, 1–47. (In Russian)
19. Loseva, E.; Osokin, A.; Mironov, D.; Dyakonov, I. Specific features of the construction and quality control of pile foundations in engineering and geological conditions of Saint Petersburg. *Archit. Eng.* **2020**, *5*, 38–45. [CrossRef]
20. Dashko, R.E.; Vlasov, D.Y.; Shidlovskaya, A.V. *Geotechnics and Subsurface Microbiota*; Publishing House of the Institute “Georekonstrukciya”: Saint Petersburg, Russia, 2014; p. 279. (In Russian)
21. Ridus. Available online: <https://www.ridus.ru/v-sankt-peterburge-uchastilis-avarii-v-kanalizacii-399141.html> (accessed on 10 August 2024).
22. Guo, B.; Liu, C.; Gibson, C.; Frigon, D. Wastewater microbial community structure and functional traits change over short timescales. *Sci. Total Environ.* **2019**, *662*, 779–785. [CrossRef]
23. LaMartina, E.L.; Mohaimani, A.A.; Newton, R.J. Urban wastewater bacterial communities assemble into seasonal steady states. *Microbiome* **2021**, *9*, 116. [CrossRef]
24. Polovnilov, V.Y.; Volynin, A.F. Geophysical and thermal analysis of soils in the zones of location of sewer collectors in St. Petersburg. *Bull. Tomsk Polytech. Univ. Geo Assets Eng.* **2022**, *333*, 81–88. (In Russian) [CrossRef]
25. David Rumsey Map Collection. Available online: <https://www.davidrumsey.com/luna/servlet/detail/RUMSEY~8~1~2289~180029:Sanitary-&-Topographical-Map-of-the> (accessed on 10 August 2024).
26. Maksomovich, N.G.; Demenev, A.D.; Khmurchik, V.T. Transformation of the Mineral Composition of Dispersed Soil under Microbiological Impact. *Bull. Perm Univ. Geol.* **2021**, *20*, 24–32. (In Russian) [CrossRef]
27. Lebedeva, Y.; Kotiukov, P.; Lange, I. Study of the Geo-Ecological State of Groundwater of Metropolitan Areas under the Conditions of Intensive Contamination Thereof. *J. Ecol. Eng.* **2020**, *21*, 157–165. [CrossRef]
28. Kobak, A.V.; Piryutko, Y.M. *Historical cemeteries of Saint Petersburg*; Center-Polygraph: Moscow, Russia, 2009; p. 797. (In Russian)
29. Gorskaya, V.A. *Engineering-Geological Analysis of the Historical Aspect of the Development and Contamination of the Underground Space of Saint Petersburg*. Ph.D. Thesis, Saint Petersburg Mining University, Saint Petersburg, Russia, 2017. Available online: [https://spmi.ru/sites/default/files/imci\\_images/sciens/dissertacii/2018/avtoreferat\\_gorskaya.pdf](https://spmi.ru/sites/default/files/imci_images/sciens/dissertacii/2018/avtoreferat_gorskaya.pdf) (accessed on 12 August 2024). (In Russian)
30. Zareczkij, Y.K. *Soil Consolidation Theory*; Nauka: Moscow, Russia, 1967; p. 270. (In Russian)

31. Pereiro, I.; Fomitcheva Khartchenko, A.; Petrini, L.; Kaigala, G.V. Nip the bubble in the bud: A guide to avoid gas nucleation in microfluidics. *Lab Chip* **2019**, *19*, 2296–2314. [\[CrossRef\]](#)
32. Nadson, G.A. *The Problem of Microbial Variability, Its Theoretical and Practical Significance*; Selkhozgiz: Moscow, Russia, 1931; p. 36. (In Russian)
33. Lee, K.-Y.; Park, S.-Y.; Kim, C.-G. Effects of radon on soil microbial community and their growth. *Environ. Eng. Res.* **2020**, *25*, 29–35. [\[CrossRef\]](#)
34. Narenkumar, J.; AlSalhi, M.S.; Prakash, A.A.; Abilaji, S.; Devanesan, S.; Rajasekar, A.; Alfuraydi, A.A. Impact and Role of Bacterial Communities on Biocorrosion of Metals Used in the Processing Industry. *ACS Omega* **2019**, *4*, 21353–21360. [\[CrossRef\]](#)
35. Little, B.J.; Blackwood, D.J.; Hinks, J.; Lauro, F.M.; Okamoto, A.; Rice, S.A.; Wade, S.A.; Flemming, H.C. Microbially influenced corrosion—Any progress? *Corros. Sci.* **2020**, *170*, 108641. [\[CrossRef\]](#)
36. Dashko, R.E.; Alekseev, I.V. On the issue of the role of the biocorrosion processes in the underground environment of megapolises. *Eng. Geol. World* **2016**, *1*, 22–29. (In Russian)
37. Duhanina, U.N. Influence of bacterial microorganisms on the development of concrete biocorrosion. *Vestn. Nauk.* **2023**, *5*, 472–476. (In Russian)
38. Cytovich, N.A.; Zareczkij, Y.K.; Maly'shev, M.V.; Abelev, M.Y.; Ter-Martirosyan, Z.G. *Forecasting the Settlement Rate of Building Foundations: Consolidation and Creep of Multiphase Soils*; Strojizdat: Moscow, Russia, 1967; p. 236. (In Russian)
39. Abelev, M.Y. *Weak Water-Saturated Clayey Soils as Building Foundations*; Strojizdat: Moscow, Russia, 1973; p. 288. (In Russian)
40. Trushko, O.V.; Trushko, V.L.; Demenkov, P.A. Arrangement of multistory underground parking garages in complex engineering and geological environment. *Int. J. Math. Eng. Manag. Sci.* **2020**, *5*, 897–912. [\[CrossRef\]](#)
41. Demenkov, P.A.; Goldobina, L.A.; Trushko, O.V. Geotechnical barrier options with changed geometric parameters. *Int. J. GEOMATE* **2020**, *19*, 58–65. [\[CrossRef\]](#)
42. Dashko, R.E.; Gorskaya, V.A. Multifactor assessment of the causes progressive destruction of the New Hermitage buildings. *Ind. Civ. Eng.* **2015**, *11*, 8–14. (In Russian)
43. Dashko, R.E.; Salnikov, P.M. Main principles of an integral monitoring for St. Isaac's Cathedral in Saint-Petersburg. In Proceedings of the International Forum-Contest of Young Researchers Topical Issues of Rational Use of Natural Resources, Saint Petersburg, Russia, 18–20 April 2018; pp. 17–22.
44. Dashko, R.E.; Karpenko, A.G. Current state of above-ground and underground structures of the Alexander Column: An integral basis for its stability. *J. Min. Inst.* **2023**, *263*, 757–773.
45. Choker, H.M.; Mustafin, M.G. Geodesic support of laser scan technology use for fixing cultural heritage objects. *Geod. Cartogr.* **2021**, *82*, 2–10. (In Russian) [\[CrossRef\]](#)
46. Hatoum, H.M.; Mustafin, M.G. Optimization of locating robotic total stations for determining the deformations of buildings and structures. *Geod. Cartogr.* **2020**, *963*, 2–13. (In Russian) [\[CrossRef\]](#)
47. Glazunov, V.V.; Ageev, A.S.; Gorelik, G.D.; Sarapulkina, T.V. Results of Comprehensive Geophysical Studies on the Search for Crypts on the Territory of Suburban Necropolis of Tauric Chersonese in the Karantinnaya Balka. *J. Min. Inst.* **2021**, *247*, 12–19. [\[CrossRef\]](#)
48. Dashko, R.E.; Nguyen, T.C. Engineering and geological substantiation of the concept and structure of complex monitoring of some architectural and historical monuments in Hanoi. *Int. Res. J.* **2017**, *4*, 57–65. (In Russian) [\[CrossRef\]](#)
49. Dashko, R.E.; Alekseev, I.V. Microbially-Induced Corrosion of Structural Materials in Underground Workings of the Yakovlev's Mine (Kursk Magnetic Anomaly, Russia). *Biosci. Biotechnol. Res. Asia* **2017**, *14*, 167–175. [\[CrossRef\]](#)
50. Dashko, R.E.; Romanov, I.S. Forecasting of mining and geological processes based on the analysis of the underground space of the Kupol deposit as a multicomponent system (Chukotka Autonomous Region, Anadyr district). *J. Min. Inst.* **2021**, *247*, 20–32. [\[CrossRef\]](#)
51. Dashko, R.E.; Vlasov, D.Y.; Romanov, I.S. Some Case Studies of Mine Support Biocorrosion in Underground Workings in Various Climatic Zones. *Russ. Met.* **2023**, *2023*, 2000–2004. [\[CrossRef\]](#)

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