The Chemical and Mineralogical Changes of Soils Composition in the Destroyed Pile Foundations of Russian Architecture Monuments (The example of the Church of St. John the Evangelist)

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Abstract. The article is concerned with the study of one of the reasons for the loss of the soils bearing capacity in the Russian architecture monuments foundations (XIV-XVII centuries). It may be caused by the formation of cavities "bootlegs" as a result of the wooden pile destruction, namely, the soils chemical and mineralogical composition changes on the piles contours. The object of the study is the Church of St. John the Evangelist in the Kamenka village, Moscow Region. The research results can be applied to other architectural monuments of the XIV-XVII centuries. The relevance of the topic is determined by the value of the Russian architecture monuments as the cultural heritage objects.

1. Introduction
When studying architectural monuments, the building should be considered not separately from the soil foundation, but as a single integrated historical natural-technical system (HNTS). For the correct management of this system a special comprehensive approach is required, which will take into account not only the engineering-geological conditions of the territory but also the design features of the monument, the history of its construction and operation and the interaction with the environment.

For buildings and structures of the XIV-XVII centuries the use of wooden piles in the foundation was characteristic when constructing foundations. First, a foundation ditch was dug out, and then wooden piles were driven into its base with a step of 25-50 cm. Further, the foundation itself was constructed. The main type of foundations at that time was strip foundations, made of boulders or blocks of natural stone. The enclosing soils or lime-sand (lime-clay) mortar were used as filler [9]. Such foundations were characterized by high it was impossible to completely fill all the caverns due to the irregular shape of individual blocks, and the lime-sand mortar, began to leach out after a while with water filtering through the foundation body.

The presence of piles under the foundations undoubtedly increased the bearing capacity of the foundation soils several times, however after a certain period of time the wood began to degrade primarily due to the influence of microorganisms in the conditions of oxygen free access through the voids in the foundation.
2. Relevance
The purpose of this work is to study the processes of changing the chemical and mineralogical composition of soils within the destructed pile foundations of monuments of Russian architecture, which affect the strength properties of soils. The relevance of the topic is determined by insufficient knowledge of this problem, which has a key impact on the soil stability of the architectural monuments’ foundation.

The presence of bootlegs from decayed wooden piles does not allow performing calculations to determine the bearing capacity of the foundation and adequately assessing the monument - geological environment system, which is necessary for taking the right measures to make design decisions to save the monument.

3. Theoretical aspects of the pile destruction process
The process of wooden piles destruction is complex and unique for each monument, since there are no identical natural conditions. However, the main stages of the pile existence can be identified (Pashkin [9]). The decomposition of wood occurs frontally from the base of the foundation - from the heads to the piles of the piles. After driving the piles, they can begin to destroy from the head to the point. This process can be accompanied by the collapsing of the walls in those intervals where the wood has already decomposed, and sometimes the walls of the so-called “bootlegs” – cavities from the pile, retain their shape. If the walls collapse, the building undergoes serious deformations. The larger the destroyed soil volume, the stronger the deformation of the structure, up to the complete collapse of the wall sections.

The process of pile destruction is complex and depends on many factors: wood characteristics, soil properties, hydrogeological, temperature and microbiological conditions, etc. However, this work is devoted to the changes in the chemical and mineralogical composition of soils, which is a consequence of the interaction of microorganisms with soils under the conditions described above.

The influence of microorganisms on wood involves the decomposition of complex organic compounds and their derivatives to simple mineral compounds (CO2, H2O, NH3, etc.) and humus-type organic substances [3]. The main groups of organic compounds in humus are: humic acids, fulvic acids, humins [8].

Most often microorganisms in soils are in an inactive state [10], but wooden piles immersed in soils are active catalysts for their activity as a source of a nutrient medium. The process of wood decay in soils occurs under the influence of the vital activity of the smallest wood-destroying fungi developing in wood [1]. In addition to wood-destroying fungi, the soils contain spores of other types of fungi, bacteria, as well as actinomycetes - a group of bacteria similar in structure to fungi, and they all decompose the organic matter in the soil. 1 g of shallow soils contains about 10^6-10^7 bacterial cells [3].

The most interesting process expression of microorganisms’ activation is the formation of biogenic and biogenically determined structural links. Biogenic structural bonds are structural bonds formed with the direct participation of microorganisms’ cells due to phenomena of a different nature - the presence of charge and the formation of electrostatic bonds, physicochemical adhesion of cells to soil particles, mechanical entanglement of particles by mycelial cells, etc. The forming biogenic bonds are weaker than the abiogenic ones in the original soils. With a decrease in biomass, the aggregates partly disintegrate and partly are retained. Biogenically determined structural bonds are structural bonds of a chemical and physicochemical nature formed due to the release of various metabolic products, including biocement. After the decline of microbiological activity, precipitation of biogenic cementing substances occurs - calcium carbonate and insoluble iron compounds. The composition of the cement depends on the specific type of biota [5].

The organic substances themselves formed as a result of the microorganisms’ action also actively interact with the mineral components of soils. As a result of complex processes organomineral compounds are formed. There is information that the formed organomineral complexes may have cementation properties: under the influence of organic acids, silicon can be removed from the crystal
lattice of clay minerals and then bind with calcium, which leads to the formation of silicon-carbonate cement [7].

4. Foundations survey results

In the fall of 2019 the employees of the construction company "Lazurit" carried out work on the study of the foundations and grounds of the foundation of the Church of St. John the Evangelist in the village of Kamenka, which was laid in 1697 and finally completed in 1707. The temple was built in the form of a single-headed quadrangle. In the years 1854-1859, a two-tier bell tower and a refectory with two aisles were attached to the existing volume of the quadrangle from the west.

The geological structure of the territory is attended by modern technogenic accumulations up to 3 m thick, the upper Quaternary cover sediments up to 2 m thick, followed by alternation of fluvioglacial and moraine deposits of the Moscow and Dnieper glaciations. Groundwater is in the depth of 15 m.

The foundations of the temple are strip, made of rubble masonry of magmatic and metamorphic rocks boulders on a lime-sand mortar. Under the temple's part built in the 19th century the foundations have a depth of 1.6 to 2.9 m, and under the historical part - 1.2 - 1.7 m. The soils of the base are Upper Quaternary cover deposits, represented by clay loam mantle with interlayers of fine sand.

Under the foot of the rubble foundations of the historical part of the 17th century, bootlegs from decayed wooden piles were opened. The length of the cavities is about 1.4 m, the diameter is 12 cm, the driving step is about 30 cm. The filling between the boulder space is a lime-sand mortar, which is leached to sand. Some glasses have completely retained their shape, while others are partially filled with enclosing soil in the upper part. Most of the length of the glasses is in mantle loams, the lower part in fluvioglacial sands.

5. Analysis of the structure of the cavities – bootlegs

Considering the identified parameters of the piles, a calculation was made to determine the tangential stresses on their contours according to the method described in the dissertation work [4] so soils should not exist for a long time. According to the results of the calculation the base soils are experiencing a load-bearing capacity deficit (BCD) equal to 15 t/m².

However, these cavities have probably existed in an open state for more than 150 years, since under the conditions of the aeration zone, wood completely decomposes in 120–150 years [9]. Despite the formed BPS, long-term existence in the open state, as well as the possible action of frost heaving forces, structurally unstable pile cavities – glasses are not destroyed. On their contours, as well as in the interpil space, chemical and mineralogical processes of soil change occur, which affect the degree of convergence of the cavity walls and are of great interest for study.

Due to the structure of mantle loams in the pores and macropores, new chemical compounds and minerals are formed by the addition of calcium hydroxide washed out from the lime-sand solution. The pores are overgrown with new mineral compounds, being adsorbed on the surface of clay minerals, which determines not only the preservation of the pile cavities, but also the general stability of the soil massif.

An analogue of this process can be one of the methods of engineering soil reclamation - the liming method. When lime and water are added to the soil, silica and alumina forming a clay soil are released and react with calcium hydroxide. The destruction of clay particles occurs with the formation of hydrosilicates and hydroaluminates, which create a skeleton that increases the strength of the soil [6].

The photograph (Fig. 1) shows cavity from two decayed wooden piles. The figure clearly shows that around the outer contour of the "bootleg" there is a zone of altered gray soil, the so-called the "gleying zone" bounded by the light orange "oxidation zone". These zones are formed due to the interaction of the soil with organic substances and microorganisms. On the walls of the cavity crusts and drip forms of the altered soil represented by clay material were found. The current situation in the area of destroyed piles is shown schematically in Fig. 2.
The driving of wooden piles in the soils located in the aeration zone causes the activation of microbiological activity in the area around the piles. The joint interaction of microorganisms and organic compounds leads to a change in the oxidizing environment to a reducing one - the pH of the environs changes from weakly alkaline to weakly acidic or acidic due to aggressive organic acids.

The gleying process takes place in this zone. There is a transition of oxide compounds Fe$^{3+}$ into ferrous Fe$^{2+}$, followed by removal of clay minerals from the crystal lattice, as well as destruction of oxide and hydroxide iron minerals and subsequent migration. Humic acids when interacting with iron and aluminum hydroxides are also capable of partially transferring them into solution. With increasing calcium concentration, they precipitate [2]. The bright ferruginous border surrounding the grayish zone indicates that part of the iron migrated and then passed into the trivalent state, while part remained in the bivalent form in the gleying zone.

The formed crusts and drip forms indicate a profound change in the original clay minerals and represent new organomineral bodies. According to the data of X-ray structural analysis, the presence of minerals dolomite and calcite was determined in the composition.

6. Conclusion

Summarizing this, the process of changing the soil structure in the area of destroyed wooden piles can be divided into several stages.

**Stage I.** At the first stage the microbiological activity starts. Ca (OH)$_2$ is introduced into the base soils from a lime-sand mortar of rubble foundations. The interaction of organic acids, metabolic
products of microorganisms with soil leads to a change in the oxidizing environment to a reducing one. An initial change in the structure of the soil occurs, expressed in the destruction of ferruginous and carbonate cement of the soil, the gradual formation of new biogenic and biogenically determined bonds, the binding of the mineral part with the organic and the formation of organomineral compounds.

**Stage II.** Gradually, with the destruction of wood, and, therefore, the depletion of nutrients for microorganisms, there is a decline in microbiological activity. Sag formations and crusts of altered soil are formed. The decline in the activity of bacteria leads to the destruction of biogenic structural bonds and an increase in the role of biogenic bonds due to the deposition of biogenic cementing substances - calcium carbonate and insoluble iron compounds.

**Stage III.** At the last stage, the strength of biogenically determined bonds increases. All remaining organic substances are firmly bound to the mineral component. The level of microorganisms’ activity is reduced to its original state. Silicon-carbonate cement is formed in the gleying zone, as well as calcite cement of the soil outside the zone of microbiological activation.

*Thus, the chemical and mineralogical changes that have occurred in the soils lead to an improvement in the strength characteristics of the massif which neutralize the effect of a weak element - open cavities on the bearing capacity of soils. This unstable system of soil-cavity-"bootlegs" forms a certain strength resource.*

It should be noted that it is difficult to identify any clear periodization of these processes, since they all operate almost simultaneously and in a complex manner. The question of the complex structure existence time this remains unclear.

A correct understanding and identification of all the parameters and conditions for the formation of a new structure will help to objectively assess the state of the foundation soils, which requires further work to study this issue.

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