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Integrated geotechnical monitoring on St. Andrew's Hill

N. Molochkova *(National Conservation Area "St. Sophia of Kyiv")*, ***L. Nishchuk*** *(National Conservation Area "St. Sophia of Kyiv")*, ***V. Saprykin**** *(State Institution "Radioenvironmental Centre of National Academy of Sciences of Ukraine")*

SUMMARY

St. Andrew's Church, built in the mid-18th century, is located on the north-eastern edge of the Starokyivske Plateau - on St. Andrew's Hill, the height of which reaches about 80 m above the Dnieper. The hill is saturated with groundwater, has steep slopes and is prone to landslides, the foundations rest on soils of different physical and mechanical characteristics, including loess. These factors were the reason for multiple repairs immediately after the construction of the church.

The last large-scale emergency response and restoration work was carried out in 2008-2020. For the successful implementation of the project, the monument received international recognition - the Europa Nostra award in 2022. As part of the first stage of the work, the soil base of St. Andrew's Hill, the foundations of the church and the improvement of the territory were strengthened, which significantly affected the subsidence of the building and the hydrogeological situation. To ensure the preservation of the monument, complex monitoring is carried out at the site, including geodetic, hydrogeological, engineering observations. The article presents the main results of monitoring in recent years, allowing to control the condition of the object in various conditions and to apply preventive protective measures in a timely manner.

Introduction. St. Andrew's Church (mid XVIII century) built in 1747–1762 according to the design of the architect Francesco Bartolomeo Rastrelli, since 1987 it has been part of the National Reserve "Sophia of Kyiv". St. Andrew's Church is an architectural monument of national importance and one of the symbols of Kiev, included in the European catalog “100 Wonders of the World” (2002). The location of the church is advantageous from an urban planning point of view, but is characterized by complex engineering and geological conditions. The complicated relief, the presence of springs and groundwater caused the construction of the church on a massive stylobate 14 meters high in the form of a pentagon. For its construction the soil was excavated and groundwater was diverted, but the springs continued to destroy the slope, causing washouts and landslides. This required constant repairs until the beginning of the 20th century, when adits were built to drain the water. Nevertheless, deformation processes on the hill and the church persisted.
Calculations of the stability of the hill revealed two landslide-prone zones: 20 m wide in the north and 50 m wide in the east, with a minimum stability coefficient of about 1.0 (below the norm according to DBN V.1.1-46:2017 (Ministry of Regional Development and Construction of Ukraine, 2018). Here, the steepness of slopes reached 43-45°, structural outcrops, soil erosion and uneven subsidence of the western and eastern parts of the church were recorded.
In 2008-2020, a large-scale project "Emergency and repair and restoration works on St. Andrew's Church" was implemented (Molochkova, 2025, p. 163). First of all, unique emergency works were carried out to strengthen the soil base of St. Andrew's Hill and the foundations of St. Andrew's Church. Due to the complexity of the work, deformations on the monument significantly intensified and the groundwater level on the hill rose. The preservation of the monument and the success of this restoration project became possible thanks to comprehensive monitoring conducted since the end of the 20th century.

Method and Theory. The main objective of protecting architectural monuments, including during repair and restoration works, is to preserve the authenticity of the monument and create favorable conditions for its further safe use. In relation to St. Andrew's Church, the implementation of such complex engineering tasks during restoration requires competent, well-founded design and technological solutions to strengthen the stability of the hill and scientific and technical support for their application. This is most effectively achieved through integrated **monitoring methods** both in the process of monitoring the monument and in the process of conducting repair and restoration works for operational control.

Examples. The first stage of the Project (2008–2012) was implemented by the Joint Venture Osnova-Solsif (Scientific and Technical Support Program, 2011), scientific support was provided by the State Enterprise Research Institute of Building Structures according to DBN V.1.2-5:2007 (Ministry of Regional Development and Construction of Ukraine, 2007). Work was carried out to strengthen the foundation base with “jet” columns, a metal belt was installed at the level of the top of the 1st floor of the stylobate, the base of the hill is reinforced with a deep retaining wall made of bored piles up to 18 m long 1020 mm in diameter with 400 mm intervals between them, a drainage system was installed to drain water from the hill, the steepness of the slopes was smoothed out, trees were uprooted from the surface of the hill, and a large system for stabilizing soil and turf was installed.

Results. All repair and restoration work were accompanied by continuous comprehensive scientific and technical monitoring, which yielded the following results:
- geodetic observations
Have been conducted since 1987 using basement marks and benchmarks. During the period of active work, subsidence amounted to 80% of the total value for the entire observation period, but occurred uniformly. After completion of the work, deformations stabilized.
- crack opening monitoring
It has been conducted since 2004 by a comparator, twice a year (in winter and summer). No observations were conducted from 2007 to 2014.

No sharp changes in the crack opening width were observed in the church during the emergency repair and restoration work. According to the data of long-term instrumental studies, the increase in the change in the crack opening width per year (during the cold period) is stable, is in a small range – 0.23 ... + 0.3 mm, the change in the crack opening width from the initial count (during the cold period) from 0.00 to 0.72 mm. In the stylobate part of the church, the crack openings and wall tilts were more significant. This prompted us to improve the project and strengthen the spatial rigidity of the building's stylobate with a powerful metal frame.

- hydrogeological observations

Have been conducted since 1995 in observation wells in the upper part of the hill, including within the location of the foundations, and in the lower part of the hill near Alley of artists. The sources of groundwater replenishment are atmospheric precipitation and leaks from utility networks; discharge occurs through drainage adits and along the slope.

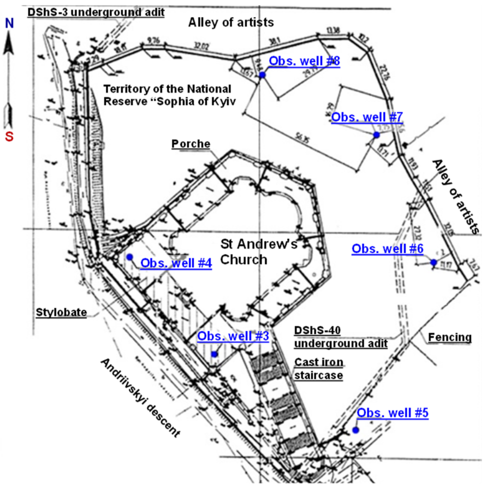

Figure 1 *Layout of hydrogeological observation wells for monitoring ground-water levels on the territory of the St. Andrew's Church Museum*

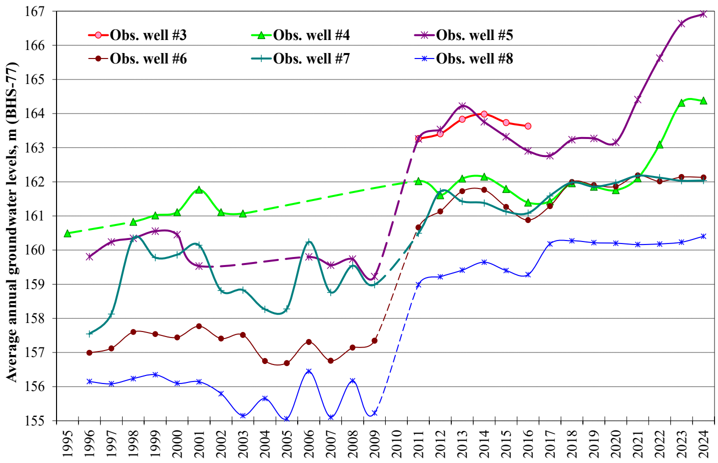

Figure 2 *Average annual groundwater level regime on the territory of St. Andrew's Church from 1995 to 2024.*

Archival data record the groundwater level in the 18th century at 165–168 m. From 1995 to 2009, it dropped to 156–163 m due to the action of adits (Figure 1, 2). In 2009–2011, the period of repair and restoration work, the level rose by 3–4 m (Saprykin et al., 2023), which is associated with several factors:

A) Water-intensive technology of constructing jet-columns to strengthen the foundation base

This process is quite water-intensive and the water in the drilled wells stood for a long time. Immediately after the completion of the work, the rise in groundwater levels in all wells could to some extent be associated with the water-intensive technology of constructing jet-columns, but these works were carried out 15 years ago and the formed water dome had already spread by that time.

B) Disruptions in water drainage

Since groundwater is diverted into the drainage adits system and in the direction of the general flow onto the slopes, the drainage system on the slope has a significant impact on the formation of the groundwater regime on the site. Due to malfunctions in the drainage system on the berm, from March 2013 to September 2015, unorganized water was diverted from the berm into trays and storm drains: some trays did not work, and water from the eastern facade either flowed into an emergency pipeline or onto a grassed hill, eroding and weakening the slope. However, since September 2015, the berm drainage system has been restored, all water from the church is diverted into storm drains in an organized manner, and the groundwater level on the slope has not decreased to the values observed before the repair and restoration works.

C) Adit condition

St. Andrew's Church and the hill on which it is located are surrounded by adit drainages of the specialized department of anti-landslide underground works. From the west and north there is the drainage adit system DShS-3, built in 1923-26 (Rybin et al., 2003). From the south there is DShS-40, built in 1969, its branch from DShS-3 is located near the lower platform of the stairs leading to the porch.

The survey of DShS-3 and DShS-40 in the protection zone of St. Andrew's Church has been carried out by the IGS NAS of Ukraine and specialists of the National reserve "Sophia of Kyiv" periodically since 1995. According to these studies, the water flow rate at the period from 2003 to 2024 in DShS-3 fluctuated from 0.32 to 3.0 m^3/day, and in DShS-40 within 8.64-27.7 m^3/day (in 2024 – 21.6 m^3/day) mainly due to natural factors. Thus, the water flow rate in adit systems has remained virtually unchanged for many years and cannot have a significant impact on the rise in groundwater level.

D) Barrage effect

A retaining wall built along the lower boundary of the hill from bored piles up to 18-20 m deep with a strip grillage created an additional obstacle to the movement of water (Figure 3). According to calculations, the rise in the groundwater level should not have exceeded 0.4 m. However, in fact, it was 3-4 m. We believe that this is the most likely reason for the rise of the groundwater level at St. Andrew's Church territory, which requires further study.

After the improvement of the hill slopes and the inclusion of the irrigation system (since 2015), the level in the lower wells rose by 1.3 m, in the upper ones - by 2.5-4 m (since 2020). Possible reasons for this may be leaks from water-bearing communications upstream and ineffective operation of the irrigation system, which creates erosion cavities up to 0.6 m on the slopes, while the volumetric soil moisture reaches 40–50%. The slope is weakened, there is a risk of local landslides. Additional construction in the adjacent area may worsen the situation.

Figure 3 *Strengthening the stability of the hill of St. Andrew's Church with the help of bored piles*

Conclusions.

1. The implementation of a set of emergency repair and restoration measures noticeably affected the subsidence of the building of St. Andrew's Church, but the increase in the subsidence of the structure (up to 80%) was almost uniform and did not lead to an increase in the deformations of the structure. After the completion of construction work, the subsidence rate significantly decreased and stabilized.
2. During the period of emergency repair and restoration works, no sharp changes in the crack width were observed in the church. In recent years, the change in the crack width per year has been stable, within a small range of -0.23 ... + 0.3 mm.

3. The groundwater regime on the hill of St. Andrew's Church is unstable. Its significant change (rise by 3-4 m) occurred mainly due to the barage effect created by bored piles along the perimeter of the hill during the first stage of repair and restoration works. The existing groundwater regime is influenced by natural and man-made factors.
4. Any new construction nearby may adversely affect the hydrogeological regime and overall stability of the slope.
5. An engineering-geological assessment of landslide hazard is recommended, taking into account the high groundwater level, soil moisture and the presence of cavities.
6. In order to prevent future waterlogging and erosion of the soil on the hill, irrigation should be minimized and drought-resistant grasses should be used.
7. To strengthen the slopes, it is advisable to plant creeping shrub vegetation.
8. It is recommended to install additional observation wells on the hill of St. Andrew's Church (with a diameter of at least 10 cm to ensure the possibility of pumping the wells) and continue integrated geotechnical monitoring.

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