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Impact of hydrogeological factors on geotechnical conditions of the Kyiv-Pechersk Lavra Monastery complex: lessons from three decades of monitoring

Impatto del dissesto idrogeologico sullo stato geotecnico del complesso del Monastero delle Grotte di Kiev: indicazioni ottenute da tre decadi di monitoraggio

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Riassunto

Il complesso architettonico del monastero delle Grotte di Kiev situato nella città di Kiev sulla riva destra del fiume Dnipro rappresenta un patrimonio storico e culturale di importanza internazionale. La revisione e l'analisi dei dati ottenuti dal monitoraggio delle acque sotterranee a partire dagli anni 90 dimostrano che i monumenti del complesso architettonico sono stati messi a repentaglio da numerose emergenze riconducibili a rischi idrogeologici collegati a fattori naturali e antropici (e talvolta ad errori di valutazione ingegneristici). Il monitoraggio e l'analisi dei dati suggeriscono un gran numero di rischi idrogeologici (inondazioni, sprofondamenti, frane, sifonamenti) ed enfatizzano l'importanza dello studio delle condizioni idrogeologiche per la salvaguardia dei monumenti architettonici in aree urbane. Questo lavoro inoltre riassume i provvedimenti ingegneristici per la mitigazione dei rischi idrogeologici e discute gli sviluppi delle future ricerche nell'area.

Abstract

The Kyiv-Pechersk Lavra monastery, located in Kyiv on the Right Bank of the Dnipro River, is a site of significant historical and cultural heritage. The review and analysis of data from the long-term (since the 1990s) groundwater monitoring studies of the Kyiv-Pechersk Lavra show that hydrogeological hazards caused by a complex combination of natural and anthropogenic factors (as well as sometimes by engineering miscalculations) have led to a significant number of emergencies that threaten the heritage architectural monuments. Monitoring and analysis of data illustrate a wide range of hydrogeological hazards (flooding, subsidence, landslides, suffusion), and emphasize the importance of consideration of hydrogeological aspects for safeguarding architectural monuments in the urbanized areas. The paper also summarizes experience in engineering measures to mitigate hydrogeological hazards and discusses future research tasks.

Introduction

The architectural ensemble of the Kyiv-Pechersk Lavra monastery, located within the city of Kyiv on the Right Bank of the Dnipro River, is a religious, historical, and cultural heritage site of international significance (no. 527 of the UNESCO World Heritage Sites List) (Petrenko, 1979; Sitkaryova, 2001). The Lavra combines unique surface structures and underground constructions from the 11th to the 19th centuries, which are integrated into the natural landscape of the Dnipro River banks slopes (Fig.1). One of the unique attractions of the Kyiv-Pechersk Lavra is the 11th-century man-made cave complexes, which were created by first inhabitants of the monastery following an example of settlements of the monastic community of the Mount Athos in Greece. The Church of the Saviour at Berestove (12th -19th centuries), the Gate Church of the Trinity (12th -18th centuries), All-Saints Church (18th century), the Great Lavra bell tower (18th century), the Dormition Cathedral (built in the 11th century, destroyed in 1941 and restored in 2000), which belong to the Lavra, are architectural and monumental art landmarks representing the result of cultural fusion of centuries-old Byzantine architectural traditions with the medieval Kyivan Rus state and the Western European Baroque.

The territory of the Lavra borders with urban development, occupies a significant area (235000 m^2), and covers various geomorphological structures on the loess plateau, slopes and the first terrace of the Dnipro River (Fig. 2). This territory has complicated geotechnical conditions and is prone to hazardous natural processes (subsidence, landslides, suffusion, erosion) as well as to human-induced hazards (leakages from the water mains, vibration loads from the city traffic, etc.), which affect the architectural monuments including underground structures (caves).

The research experience in urban hydrology shows that groundwater is a dynamic component of the geological environment and it can cause and/or enhance geological hazards such as landslides, subsidence, flooding, etc. (Hayashi et al., 2009; Colombo et al., 2018; Coda et al., 2023). Therefore, studies of geological and hydrogeological conditions are essential for monitoring and management of historical heritage sites (De Beer, 2015; Rybin et al., 2016; Ortiz et al., 2016; De Finis et al., 2017; Napo et al., 2021). The purpose of this study is to review and analyze data from the long-term hydrogeological monitoring of the Kyiv-Pechersk Lavra, which serves as the basis for identifying geological and hydrogeological hazards threatening architectural monuments. The article also summarizes experience in engineering measures aimed at mitigating hydrogeological hazards and discusses the pending research tasks.

Materials and Methods

Study site description

Morphology of the Kyiv-Pechersk Lavra complex

The architectural monuments of the Kyiv-Pechersk Lavra are located within the accumulative-denudation loess plateau with elevations of 170 – 198 m gently sloping eastwards (Upper Lavra). The plateau's surface is divided into two almost equal parts by the deep (up to 80 m) ravine (Lavrsky Ravine). The sites of Lower Lavra are located on the slopes of the Kyiv loess plateau and within the Near-Dnipro lowland on the first floodplain terrace of the Dnipro River (see Fig. 2).

The average steepness of slopes is 23 – 26° with elevations ranging from 118 to 170 m. Modern relief is formed by natural processes (landslides, erosion caused by temporary watercourses) combined with centuries-spanning human activities, such as the construction of defensive fortifications, religious and secular buildings, retaining walls, etc. A significant part of the territory of Lavra is situated within landslides and landslide-prone zones (Starostenko et al., 2006; Demchyshyn & Kril, 2019; Kril & Shekhunova, 2019; Kril & Cherevko, 2023).

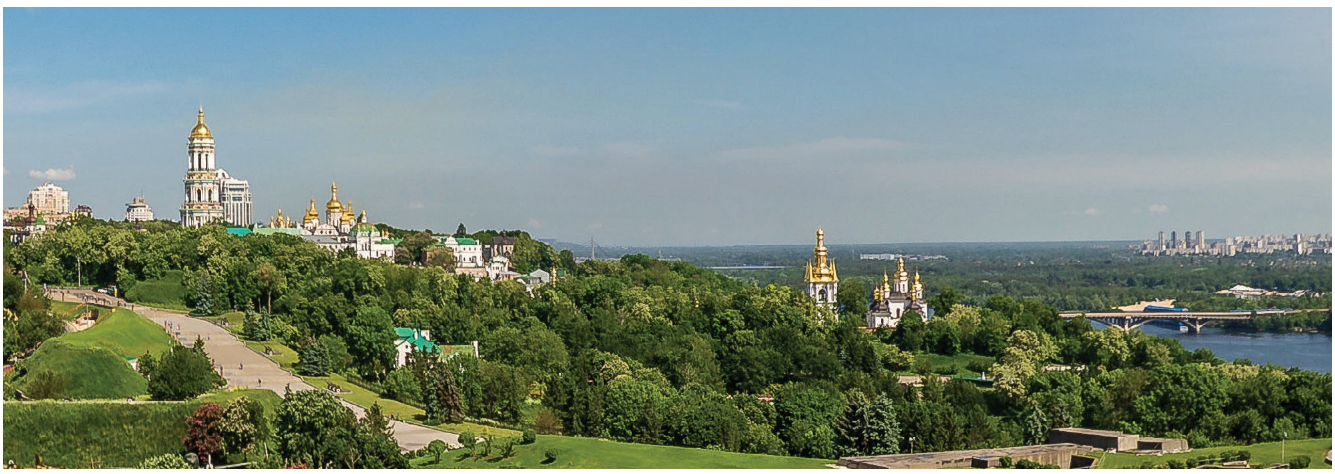

Fig. 1 - Panoramic photo of Kyiv-Pechersk Lavra on the right bank of the Dnipro River (view from southwest direction). Photo is courtesy of Mr. Yuri Koganov, National Preserve Kyiv-Pechersk Lavra (taken in June 2019).

Fig. 1 - Fotografia panoramica del monastero delle Grotte di Kiev sulla riva destra del fiume Dnipro (vista da sudovest). La fotografia è stata scattata dal sig. Yuri Koganov, museo nazional Kyiv-Pechersk Lavra (scattata nel mese di Giugno 2019).

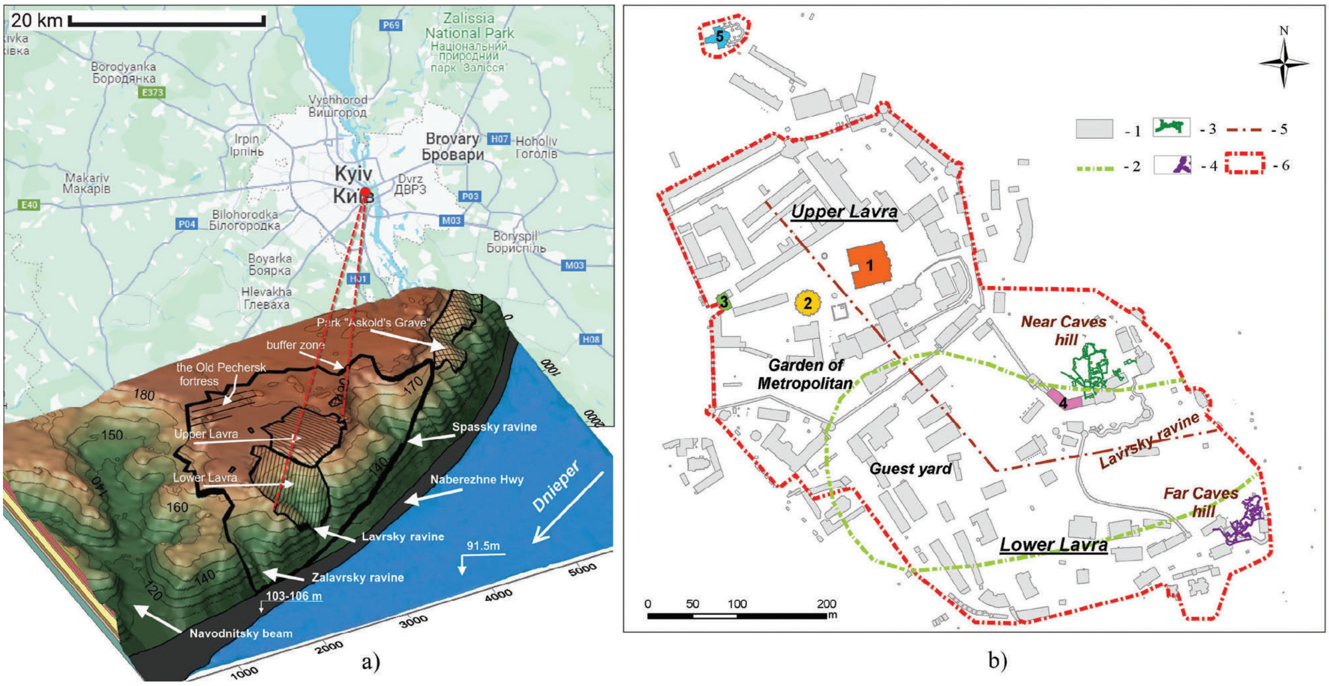

Fig. 2 - Overview scheme of the Kyiv-Pechersk Lavra within the Kyiv City agglomeration including the 3D relief model (a) and a scheme of the territory showing the main heritage sites (b). Legend: 1 - buildings, 2 - outline of the Lavrsky Ravine, 3 - Near Caves galleries, 4 – Far Caves galleries, 5 –trace of the geological section, 6 –boundary of Lavra. Notation of main architectural monuments: I- The Dormition Cathedral, II - The Great Lavra Bell Tower, III- The Gate Church of the Trinity, IV - The All-Saints Church, V- The Saviour at Berestove Church.

Fig. 2 - Panoramica del monastero delle Grotte di Kiev all'interno dell'agglomerato urbano della citta di Kiev che riporta il modello 3D del terreno (a) ed una pianta del complesso (b). Legenda: 1 – edifici, 2 – estensione della gola Lavrsky (Lavrsky Ravine), 3 – gallerie "Near Caves", 4 – gallerie "Far Caves", 5 – traccia della sezione geologica, 6 – estensione del complesso. Notazione dei principali monumenti: I – Cattedrale della Dormizione, II – Torre campanaria della Lavra, III – Chiesa della Trinità, IV – Chiesa di Tutti i Santi, V – Chiesa del Salvatore in Berestovo.

Geological settings

Concerning geological structure, this area belongs to the Pechersk anticlinal uplift. The geological setting of the study area is typical for the Kyiv loess plateau. The man-made layer (*tH*) with an average thickness of 1–3 m is underlain by the 10–14 m thick loess deposits (e,dvP_{III}). These deposits continuously cover the plateau and are absent only on the Dnipro slopes and the Lavra Ravine. Layers of Quaternary glacial deposits represented by loams, sandy loams, and sands lie below. These deposits are underlain by Pliocene-Lower Quaternary brown clays, which are deposited on the top of a 5–12 m thick bed of Miocene-Pliocene variegated clays ($N_{1\text{-}2}sg\text{-}\check{c}b$). These clays are underlain by the Novopetrivska suite sandstones and Neogene sands (N_1np), and by the Kharkiv Oligocene sands (P_3mz+ob), the latter being underlain by low permeability Paleogene Kyiv clays and marls (P_2kv). The fill-up and diluvial soils ($dvP_{III}\text{-}H$) are on the slopes (Rybin et al., 1991; 2004). A geological and hydrogeological cross section of the territory is shown in Figure 3.

Hydrogeological settings

The hydrogeological setting of Kyiv corresponds to the AGC (Alluvial Groundwater Cities) category of urban groundwater classification, as defined by La Vigna (2022). The sequence and geometry of aquifers in such a hydrogeological context are determined by the multilayer composition of sedimentary deposits.

The aquifers essential in this study are hosted in (Rybin et al., 1991; 2004; Cherevko et al., 2022): (1) the Quaternary aeolian-diluvial and lacustrine-glacial deposits on the plateau (the Upper Lavra, the upper parts of slopes, the Guest Yard, the Far Caves Hill), (2) the Quaternary diluvial soils on slopes, and (3) the Oligocene (Kharkiv) sands (everywhere throughout the site) (see Fig. 3). The aquifers (1) and (2) are hydraulically interconnected. It should be noted that the area of the aquifer in the Quaternary diluvial soils increases seasonally forming a temporary perched aquifer. This aquifer, which usually exists for a period of up to 7 months after the snowmelt, is formed on top of the low permeable geological layers (moraine loams, brown and mottled clays) within the territory of the Lower Lavra. The typical depth of its groundwater table is from 0.4 to 3.0 m.

The architectural monuments within the territory of Lavra are affected by the phreatic aquifers in Quaternary deposits. Table 1 summarizes the characteristics of these aquifers.

The depths of the Quaternary aquifer within the plateau typically range from 12 to 18 m. This aquifer is recharged by atmospheric precipitation and leakages from the water mains. Groundwater discharges into the drainage systems and the aquifer in diluvial landslide soils on slopes. The latter is located within the slopes as a 100 – 500 m wide strip along the plateau. The groundwater here saturates the mixed sand-clay deposits that have slipped from the upper areas of the plateau. The depth of the groundwater table ranges from 1

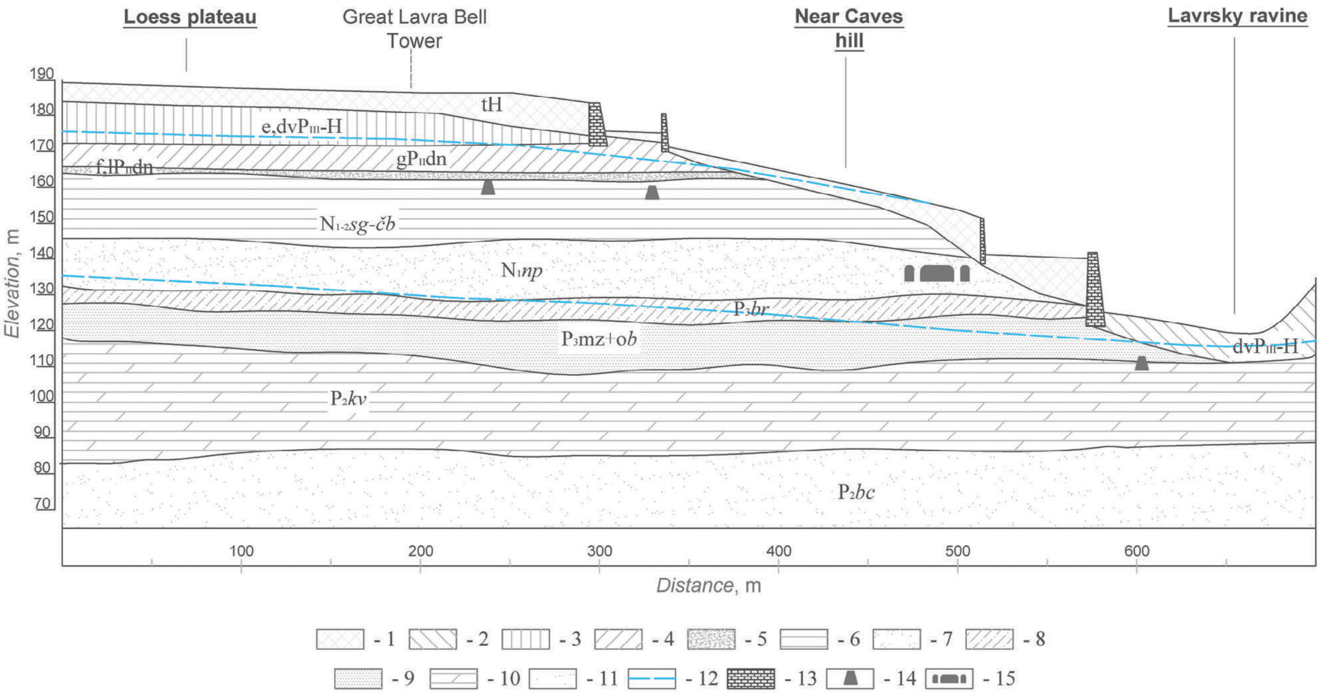

Fig. 3 - Geological and hydrogeological section of the territory of the Kyiv-Pechersk Lavra. (Trace of the section is shown in Fig.1). Legend: 1 – man-made deposits (tH), 2 – diluvial deposits on slopes (dvP_{III}-H), 3 – loess soils (e,dvP_{III}-H), 4 – moraine deposits (sand, sandy loams, loams), ($gP_{II}dn$), 5 – fluvioglacial sands, (f,$lP_{II}dn$), 6 – brown clays, (N_1-2sg-čb), 7 – sandy loams and sands of Novopetrivska suite, (N_1np), 8 – sands and sandy loams of Berekska suite, (P_2br), 9 – sands of Kharkiv suite, (P_3mz+ob), 10 – clay marls, (P_2kv), 11 – sands of Buchack suite, (P_2bc), 12 – aquifers in Quaternary deposits (first from the surface) and Oligocene sands (second from the surface), 13 – engineered structures – retaining walls, 14 – drainage systems, 15 - caves.

Fig. 3 - Sezione geologica e idrogeologica dell'area del monastero delle Grotte di Kiev (traccia della sezione in Fig. 1). Legenda: 1 – depositi antropici (tH), 2 – depositi alluvionali sul versante (dvP_{III}-H), 3 – loess (e,dvP_{III}-H), 4 – depositi morenici (sabia, limi sabbiosi, limi) ($gP_{II}dn$), 5 – sabbie fluvioglaciali (f,$lP_{II}dn$), 6 – argille plastiche marroni (N_1-2sg-čb), 7 – limi sabbiosi e sabbie della sequenza di Novopetrivska (N_1np), 8 – sabbie e limi sabbiosi della sequenza di Berekska (P_2br), 9 – sabbie della sequenza di Kharkiv (P_3mz+ob), 10 – marne argillose (P_2kv), 11 – sabbie della sequenza di Buchack (P_2bc), 12 – acquiferi situati nei depositi Quaternari (primo dalla superficie) e nelle sabbie Oligoceniche (secondo a partire dalla superficie), 13 – muri di contenimento, 14 – sistemi di drenaggio, 15 – grotte.

Tab. 1 - Characteristics of the aquifers in Quaternary deposits within the study area.

Tab. 1 - Caratteristiche degli acquiferi Quaternari all'interno dell'area di studio.

Aquifer	Water-bearing deposits	Thickness of the horizon, m	Typical elevations of groundwater level, m	Hydraulic conductivity, m/day
Quaternary aeolian-diluvial and lacustrine-glacial deposits (plateau)	Fluvioglacial loams, sandy loams, sands, loess loams	2 – 18	169 - 181	loam – 0.05 – 0.5; sand – 2 –8
Quaternary diluvial soils (slopes)	Sandy loams, loams, sands	5 – 10	150 - 172	0.05 – 2
Quaternary diluvial soils (Lower Lavra, temporary)	Sandy loams, loams, sands	1–2.5	145-160	0.05-1

to 6 m, more often 3 – 5 m. The aquitards for Quaternary aquifers on the plateau and in the upper part of the slopes are represented by the layers of brown and variegated clays, by the clay varieties of landslide soils in the middle part, and by the Kyiv marl clays in the lower part. The groundwater discharge occurs in the form of springs, by inflow to the shallow drainage systems, evapotranspiration on the slopes, and vertical inflow to the Kharkiv aquifer located below.

Anthropogenic impacts on hydrogeological and geotechnical conditions

It should be noted that the complicated natural topography and geotechnical conditions within the boundaries of the Kyiv-Pechersk Lavra were significantly influenced by anthropogenic factors. The human activities over many centuries included terracing and reinforcing the Dnipro slopes by constructing retaining walls (with a total length of more than 5 km; Figure S1 in SI), subsurface drainage systems, surface stormwater collectors (with the total length of more than 10 km; Figure S2 in SI) and other man-made structures. However, the construction of against-landslide structures and drainages was often carried out randomly, without properly considering the hydrogeological and geotechnical features of the territory (Demchyshyn & Kril, 2019). In addition, the territory of

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Lavra is covered by extensive systems of water mains (water supply lines, heating water pipelines, and sewage collectors with a total length of about 13 km), which is typical for the urbanized groundwater context (Figure S3 in SI).

Methods of hydrogeological investigations

Groundwater monitoring system

The groundwater monitoring well network in the territory of the Kyiv-Pechersk Lavra was established in the early 1990s and has been gradually expanded in the later period (Rybin et al., 2004; Starostenko et al., 2006). Currently, it includes 48 monitoring wells (Cherevko et al., 2022) (Fig. 4). Initially, the observation wells were equipped with steel casing, later with PVC casing. The wells have a diameter of 80 – 108 mm and 1-4 m long screens (technical specification of representative wells are given in SI, Figures S4 – S6). The groundwater level measurements are primarily carried out manually. The frequency of groundwater level measurements is usually 1 – 4 times per month. Groundwater sampling for geochemical analyses (major ions) is carried out occasionally (the last survey was conducted in 2018). Groundwater monitoring is carried out by the Department of Monitoring of the territory and monuments of the National Preserve "Kyiv-Pechersk Lavra.

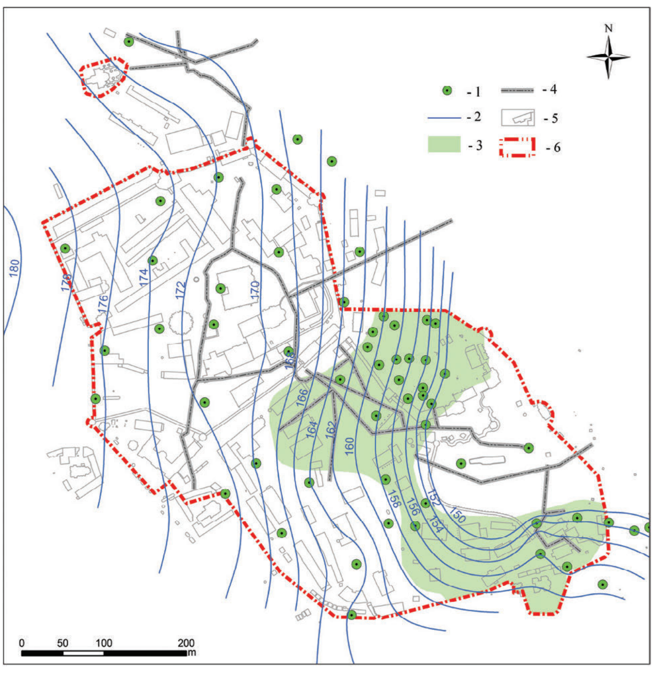

Fig. 4 - Schematic map of the groundwater monitoring well network of the Kyiv-Pechersk Lavra and distribution of groundwater levels in the aquifer in Quaternary deposits. Legend: 1 – monitoring wells, 2- groundwater levels in the aquifer in Quaternary deposits (March 2023), 3 – area of the temporary (seasonal) aquifer in Quaternary deposits, 4 – deep drainage systems, 5 – buildings, 6 – boundary of Lavra.

Fig. 4 - Carta schematica della rete di monitoraggio del monastero delle Grotte di Kiev e distribuzione dei livelli piezometrici negli acquiferi Quaternari. Legenda: 1 – pozzi della rete di monitoraggio, 2 – livello piezometrico dell'acquifero Quaternario (Marzo 2023), 3 – area interessata dallo sviluppo di un acquifero stagionale nei depositi Quaternari, 4 – sistemi profondi di drenaggio, 5 – edifici, 6 – estensione del complesso.

Information on the roles of various stakeholders in monitoring geological hazards and planning mitigative measures at Kyiv-Pechersk Lavra is given in Section 3 of SI.

Geophysical studies

Geophysical methods were used to study the geological environment of Lavra, including cave complexes. The objectives were to characterize the soil moisture content and soil density in the borehole profiles; to detect the presence of subsurface voids and/or structural disturbances of soil layers, etc. The geophysical methods included neutron-logging techniques, geoelectric and seismo-acoustic methods, in particular the electromagnetic short-pulse (EM), vertical electrical soundings (VES), seismic-acoustic and ground-penetrating radar surveys (Rybin et al., 2004; Starostenko et al., 2006; Levashov et al., 2007). Moisture in the unsaturated soil profiles was studied using tensiometers and soil moisture sensors (Rybin et al., 2004; Skalsky et al., 2007). Additional information about the geophysical methods used to study the Kyiv-Pechersk Lavra is given in Section 4 of SI.

Groundwater modeling

To interpret the groundwater monitoring data in the Kyiv-Pechersk Lavra, assess the consequences of potential accidental scenarios, and substantiate mitigative measures, several authors used mathematical modeling of flow in the vadose zone soils (Rybin et al., 2004) and/or the 2D / 3D modeling of groundwater flow in the aquifers using the MODFLOW code (Rybin et al., 2001; Starostenko et al., 2006). Information on groundwater modeling of the Kyiv-Pechersk Lavra is provided in Section 5 of SI.

Results and discussion

Impact of groundwater on the geotechnical conditions of foundations of architectural monuments

The main architectural monuments of the Kyiv-Pechersk Lavra are on the plateau within the Upper Lavra (see Fig. 1). The foundations of these monuments are established in loess-type sandy loams. In natural conditions, the loess soils have a relatively high (42-46%) porosity and an under-compacted soil structure. Low soil moisture content loess-type sandy loams have sufficient resistance to load and serve as a reliable foundation for buildings. However, with an increase in the soil moisture content, loess soils become compacted and subject to subsidence. The loess soils are also prone to mechanical suffusion at high groundwater flow rates (e.g., in case of incidents on water mains) (Rybin et al., 2004).

The most important monuments of Lavra include the Near Caves and the Far (Varyagian) Caves carved in the kaolinite sandstones of the Novopetrivska Formation (with the absolute elevations of the floor 140 – 145 m) situated respectively on the left and right sides of the Lavra Ravine. In their natural state the sandstones are in dry condition, as they are covered from above by a low permeable layer of brown and mottled clays, while the groundwater level in the aquifer in the Kharkiv sands, which is situated below the caves, is located at 16 – 18 m below the cave floor (see Fig. 3). In a dry state (the soil moisture content of 2 – 5%) the local sandstones have high elastic properties. However, with the increase of soil water content (above 5%), the sandstone loses its elastic properties and turns into sand. The sandstone can restore its stiffness when dried (Brilling, 1990; Rybin et al., 1991; Starostenko et al., 2006).

An excessive soil water content is the critical factor that initiates the landslide processes on the Dnipro slopes around the Kyiv-Pecherska Lavra (Lichkov, 2021; Demchyshyn & Kril, 2019), in particular in the Far Caves Hill (Kril & Cherevko, 2023). The processes of suffusion caused by the washout by infiltrating water fluxes of small particles from the soil have also become widespread within the Lavra, resulting in soil depressions and sinkholes. The suffusion sinkholes are usually located near modern or ancient underground structures.

Thus, hydrogeological conditions and the resulting moisture content in soils represent a critical factor that can severely impact the geotechnical soil properties and can cause deformation or even ruination of the heritage structures (Rybin et al., 2004; Starostenko et al., 2006; Cherevko et al., 2009, 2017).

Groundwater level regime

The groundwater level regime in the study area is determined by seasonal climatic factors and by leakages from the water mains (water supply, heating water pipelines, sewage systems), drainage systems and engineered structures (pile foundations, subsurface basements of retaining walls, etc.) (Starostenko et al., 2006; Cherevko et al., 2009, 2017, 2022).

Distributions of the permanent (within the plateau) and the temporary (on the slopes) Quaternary aquifer are shown in Figure 4. Groundwater level fluctuations of the Quaternary aquifer in the Upper Lavra are cyclic with the annual amplitude usually not exceeding 0.5–1.0 m. The highest levels are observed in the spring, and the lowest in the autumn-winter period. However, in the case of accidental leakages from water mains, groundwater level can abruptly rise to 2 - 4.5 m. In recent years, long-term rises in the groundwater level have been recorded in wells on the northwestern perimeter of the Upper Lavra, where the territory of Lavra borders urban development with the city water mains. Significant rises in groundwater level threaten water saturation and subsidence of loess deposits within the flooded geological layers.

Groundwater levels in the diluvial soils located on the slopes of the plateau and Lavra Ravine are situated at significantly lower depths compared to the Upper Lavra (see Table 1). In the case of shallow groundwater levels, even short-term precipitation or snowmelt events can lead to an abrupt groundwater level rise in the range from 0.1 – 0.2 m to 1 – 1.5 m depending on the soil lithology and drainage conditions (Fig. S4 in SI). Shallow depths to groundwater level within the Lower Lavra create a threat of direct flooding of foundations of buildings (in case of extreme meteorological events, water mains incidents, etc.).

Hydrogeological factors threatening the preservation of architectural monuments

Long-term monitoring studies on the territory of Lavra revealed the following main factors threatening the geotechnical conditions of architectural monuments (Rybin et al., 2004; Starostenko et al., 2006; Cherevko et al., 2009, 2017; Demchyshyn & Kril, 2019): (1) accidental leakages from the water mains; (2) uncontrolled inflows of groundwater from the adjacent urbanized areas; (3) barrage (subsurface barrier) effects from foundations (e.g., when constructing buildings using subsurface pile foundations) and from retaining walls; (4) accumulation and infiltration to the geological environment of surface runoff (e.g., following a seasonal accumulation and subsequent melting of snow etc.); (5) malfunctioning, siltation of drainage systems on slopes and/or of the storm sewer collectors; (6) poorly planned or implemented repair and restoration works (leading, for example, to the development of preferential flow paths through the low permeable layers, or disrupting the functioning of the existing drainage systems).

According to our assessment, 11 major accidents caused by leakages from the water mains occurred within the Lavra and the surrounding area from 1993 to 2023 (Table S1, Fig.S3 in SI).

The above-mentioned accidents led to the formation of the perched aquifer, sharp rises in groundwater levels, flooding of foundations, water saturation, deformation of building walls, etc. In 1994, a heating water pipeline breakdown on the Economic Yard of the Upper Lavra territory led to the rise of groundwater level by 4.6 m. The water main accidents in 1998 – 2008 led to groundwater level rises of 1.5 – 2.4 m. This resulted in water saturation of the lower part of the loess soil strata, its compaction, and uneven subsidence of foundations of buildings with the formation of structural cracks (Figures S9-S11 in SI). The last large-scale emergency occurred on 27 October 2022 because of accidental leakage from the heating water pipeline, which runs across the Upper Lavra through the territory of the Metropolitan's Garden. As a result, three large (up to 2 m deep) sinkholes were formed on the ground surface with a total area of 140 – 150 m^2. The underground structure – "Metropolitan's Wine Cellar" was flooded entirely and partially ruined (Fig. 5).

Another example of the development of hazardous hydrogeological processes is the poorly implemented restoration work on the territory of the Lower Lavra in 2004 – 2008, during which a part of the drainage system of the Guest Yard was disabled. This drainage system was constructed with the buildings of the Guest Yard in the 19th century and it regulated the hydrogeological situation in this location during high groundwater levels for almost a century and a half. The destruction of the drainage system resulted in the flooding of parts of the foundations of the local buildings.

Until the end of 2023, the processes of flooding by groundwater and surface water have resulted in adverse impacts on the geotechnical condition of 57 architectural monuments (including cave complexes) of the Kyiv Pechersk Lavra; the subsidence processes have led to deformations of 17 buildings; activation of landslide processes has affected 17

Fig. 5 - Photographs of sinkholes in the territory of the Metropolitan's Garden and the soil suffusion in the Metropolitan's Wine Cellar caused by the accident in October 2022.

Fig. 5 - Fotografie dei sinkholes nell'area dei Giardini Metropolitani e dei sifonamenti nella Cantina Metropolitana causate dagli eventi dell'ottobre 2022.

buildings; in 11 cases soil suffusion processes have led to the formation of sinkholes and subsidence, leading to deformations of the underground structures). The generalized scheme of manifestations of dangerous geological and hydrogeological processes within the Kyiv-Pechersk Lavra is shown in Fig. 6.

Impacts of hydrogeological processes on the Near Caves

In recent decades, problems of flooding by groundwater of cave complexes, which represent the most important historical and religious attractions of the Kyiv-Pechersk Lavra, have reached a threatening scale (Rybin et al., 2004, 2013; Starostenko et al., 2006; Cherevko et al., 2009, 2015, 2017; Kril & Cherevko, 2023). The problems of the Near Caves caused by hazardous hydrogeological factors are discussed in more detail below.

The Near Caves are located on the southern slope of Near Caves Hill in a layer of Novopetrivsky sandstones, covered from the top with a low permeable layer of brown and mottled clays. The surface of the hill is covered with a fruit and berry garden, which is cultivated by monks (Fig. 7). Flooding of caves often occurred during the spring snowmelt, and less frequently during long rainy periods. The caves located at a

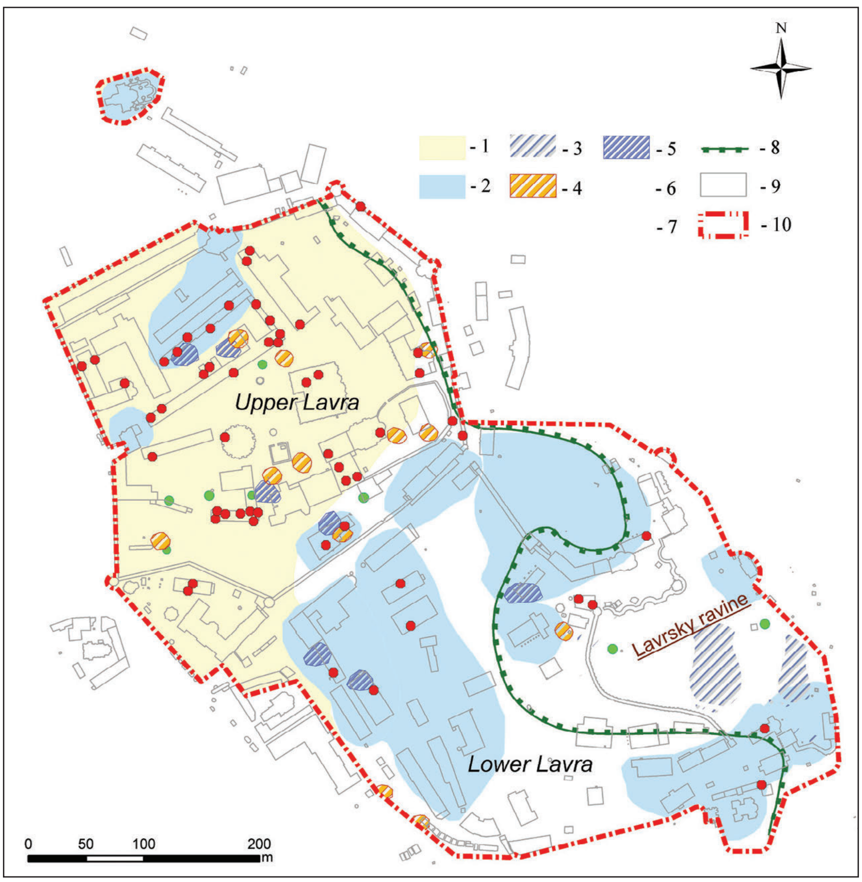

Fig. 6 - Schematic map of hazardous geological and hydrogeological processes in the Kyiv-Pechersk Lavra. Legend: 1- zone of potential subsidence, 2 – flooding by groundwater, 3 – stabilized landslides, 4 – suffusion sinkholes, 5 – flooding by surface water, 6 – manifestation of deformations and cracks in buildings, 7 – subsidence sites and sinkholes, 8 – boundary of landslide hazard zone, 9 – buildings, 10 – boundaries of Lavra.

Fig. 6 - Mappa schematica dei rischi geologici e idrogeologici nell'area del monastero delle Grotte di Kiev. Legenda: 1 – zona con subsidenza potenziale, 2 – allagamento da parte di acque sotterranee, 3 – frane stabilizzate, 4 – sifonamenti, 5 – inondazione da parte di acque superficiali, 6 – deformazioni e fessurazioni di edifici, 7 – zone affette da subsidenza e sinkholes, 8 – limite delle zone a rischio di frane, 9 – edifici, 10 – estensione del complesso.

shallow depth from 2 to 8 m are the most affected. Repeated emergencies were caused by unfavorable combinations of natural (meteorological) and/or anthropogenic factors (for example, by the excessive garden watering by monks in 2005). In 1988, a collapse occurred in the walls and the vault of the entrance gallery to the Near Caves due to the excessive water saturation of surrounding soils. In May 2005, the soil fallout (with a volume of up to 10 m^3) occurred in the underground Batyi Gallery with the collapse of the vault. It is believed that the factor that provoked the emergency was the monks' excessive irrigation of the garden on the top of the hill (Starostenko et al., 2006; Cherevko et al., 2009). In March 2013, an accidental water ingress to the caves due to seepage through the vault and ventilation hole in the Bisnuvatykh Gallery occurred (see Fig. 7). In March 2008 and February 2009, the soils in the section of the restored Batyi Gallery were saturated due to the infiltration of atmospheric precipitation through the insufficiently compacted soil of a pit, which was excavated in clay layer to mitigate the consequences of the 2005 accident. This infiltration resulted in a repeated cave ruination process (Cherevko et al., 2015).

A program of hydrogeological monitoring studies and

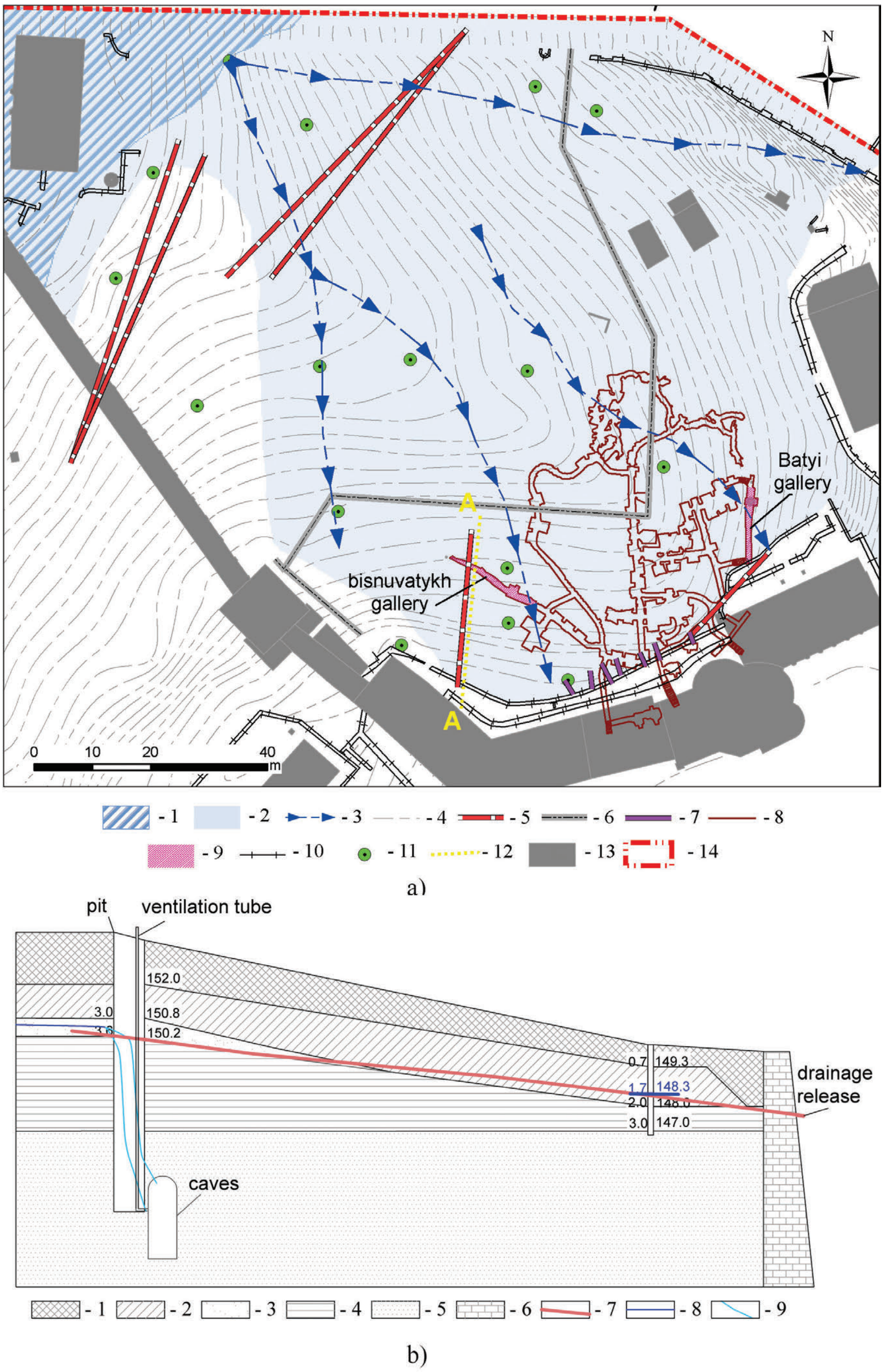

Fig. 7 - (a) Scheme of hydrogeological conditions, locations of accidents, and engineering mitigation measures at the Near Caves site. Legend: 1 – zone of the permanent aquifer in Quaternary deposits, 2 – zone of the temporary aquifer (as on March 03, 2019), 3 – groundwater preferential flow path lines, 4 – ground surface isolines, 5 – horizontal drainage, 6 – surface stormwater apron, 7 – drainage holes in the retaining walls, 8 – cave galleries, 9 – locations of accidents in caves, 10 – retaining walls, 11 – monitoring wells, 12 – line of the geological section A-A; 13 - buildings; 14 – boundary of Lavra. (b) - Geologic cross-section along the A-A line: 1 – man-made soils, 2 – diluvial soils (clay loams, sandy loams), 3 - diluvial soils – sands with interbeds of clay loams, 4 – brown clays, 5 - sandstones, 6 – retaining wall, 7 – horizontal drainage, 8 – groundwater level, 9 – pathways of inflow of groundwater to caves before construction of drainages.

Fig. 7 - (a) Mappa schematica dell'area circostante il sito "Near Caves" che riporta l'assetto idrogeologico, la posizione degli incidenti avvenuti nell'area e le misure ingegneristiche adottate per la mitigazione del rischio. Legenda: 1 – estensione dell'acquifero Quaternario, 2 – area interessata dallo sviluppo di un acquifero temporaneo (come avvenuto il 3 marzo 2019), 3 – linee di flusso preferenziale delle acque sotterranee, 4 – isoipse, 5 – drenaggio orizzontale, 6 – canaletta di scolo delle acque piovane, 7 – drenaggi nei muri di contenimento, 8 – gallerie, 9 – porzioni delle gallerie interessate da incidenti, 10 – muri di contenimento, 11 - pozzi di monitoraggio, 12 – traccia della sezione geologica A-A, 13 – edifici, 14- estensione del complesso. (b) Sezione geologica A-A. Legenda: 1 – depositi antropici, 2 – depositi alluvionali (limi argillosi, limi sabbiosi), 3 – depositi alluvionali (sabbie con interstrati di limi argillosi), 4 – argille plastiche, 5 – arenarie, 6 – muri di contenimento, 7 – drenaggio orizzontale, 8 – livello piezometrico dell'acquifero, 9 – direzione preferenziale di infiltrazione delle acque sotterranee nelle grotte prima della costruzione dei drenaggi.

geophysical surveys aimed at investigating the cause of emergency allowed to develop the following conceptual model of ingress of groundwater to the Near Caves (Starostenko et al., 2007; Cherevko et al., 2015, 2017). The permanent groundwater aquifer in Quaternary deposits is present only in the upper part of the Near Caves Hill (see Fig.7). In the rest of the territory, groundwater occurs temporarily as it spreads over the surface of the low permeable clay layers under influences of seasonal rainfall or snowmelt. In general, the formation of this temporary aquifer occurs due to the infiltration of atmospheric precipitation (the main component), the lateral inflow of groundwater from the territory of the Upper Lavra, and losses from local water networks (e.g., storm drains). The seasonal and episodic (caused by the anthropogenic factors) infiltration recharge leads to the lateral spread of groundwater towards the cave tunnels, which are located downslope, along the preferential flow paths in permeable lenses of sandy loams and loams overlying the eroded surface of brown and variegated clays. The groundwater accumulation above the caves is caused by water retention due to the retaining walls ("barrage effect") along the southern and southeastern perimeter of Near Caves Hill. In addition, infiltration of groundwater into the cave complexes can occur through the preferential flow paths in the clay layer above the caves, which were created due to natural (landslide-induced cracks) or anthropogenic factors (e.g., in the ventilation hole to the caves, or through insufficiently compacted soil in the pit excavated for the repair works). The conducted research allowed the development of mitigation measures for the Near Caves.

Measures for protecting the heritage sites from flooding

The following measures are proposed to protect the architectural monuments and cave complexes of Lavra from hazardous hydrogeological processes (Rybin et al., 2004, 2013; Starostenko et al., 2006; Cherevko et al., 2009, 2015, 2017; Demchyshyn & Kril, 2019):

- replacement (reconstruction, repairs) of water mains, including those situated in the adjacent urban territory;
- development and implementation of groundwater drainage designs (e.g., installing shallow subsurface drainage systems);
- construction of discharge outlets (drainage or weep holes) in the retaining walls and deep subsurface foundations to mitigate groundwater "barrage effects";
- proper management of surface runoff (i.e., reconstruction of existing and installation of new storm-water sewer systems, etc.);
- repairs and desilting of the deep aquifer drainage systems on the hillslopes of the Dnipro River;
- waterproofing of the building foundations with the accompanying (if necessary) installation of shallow drains and construction and maintenance of "light gaps" between the walls of buildings and surrounding soil massif for air drying.

When developing mitigation measures for specific heritage structures, an individual site-specific approach is needed, but it is also necessary to solve problems comprehensively considering mutual influences and interdependence between various structures.

Below are listed examples of mitigative measures that have been implemented in the last decade. In 2014 – 2016, groundwater drainage was carried out in Near Caves's garden. From February to May 2014, horizontal drainage was installed in the upper part of the garden across the main groundwater flow direction along the surface of the clay layer. At the same time, four discharge outlets (hydro-augers) were constructed in the retaining wall where the most significant flooding near the caves occurred (Fig.S12 in SI). In 2016, work was carried out to divert the groundwater flow from the vent that enters the Bisnuvatykh Gallery (a probable groundwater pathway to the sandstone strata). In parallel, additional groundwater discharge outlets were constructed in the retaining walls and horizontal drainage was installed in the northern part of the garden (Cherevko et al., 2015, 2017) (Fig. 7). These works improved the hydrogeological situation, and new instances of water ingress to caves were not observed from 2015 to 2022 in the area located near the retaining walls in the lower part of the slope. Despite winters with significant snow cover, water seepage to the Bisnuvatykh Gallery hasn't been observed since 2019.

Flooding of the foundation of several buildings in the territory of the Guest Yard was observed during the last decade leading to excessive water saturation of building structures, plaster wall destruction, etc. In 2015 – 2018, shallow horizontal drainages were constructed on this site. At the same time, the foundations of buildings were waterproofed. As a result, the buildings that suffered from foundation flooding were successfully dewatered, and the groundwater levels in the observation wells in this area decreased by 0.6 – 0.9 m.

Conclusions

The experience of monitoring studies of the Kyiv-Pechersk Lavra demonstrates a wide range of hazardous hydrogeological processes. It highlights the importance of considering hydrogeological aspects in safeguarding heritage sites situated in urbanized areas. Hazardous hydrogeological processes caused by a complicated combination of natural and anthropogenic factors, and sometimes by engineering miscalculations, have led to many emergencies that impacted the heritage architectural monuments.

In recent years, several successful mitigative measures have been implemented on the territory of the Kyiv-Pechersk Lavra such as: (1) the installation of a system of shallow horizontal drainages in the Near Cave Hill and in the Guest Yard of the Lower Lavra; (2) installation of drains along foundations; a partial replacement of water supply pipelines networks on the territory of the Lower Lavra; (3) re-laying of the municipal network of storm sewers outside the territory of the Lavra; (4) construction of groundwater discharge holes in the retaining walls, etc.

However, complicated natural and anthropogenic conditions and a significant number of structures with manifestations of dangerous processes (see Fig. 6) require further targeted efforts to solve the geotechnical problems of Lavra. The problems of safeguarding the heritage objects of the Kyiv-Pechersk Lavra from hydrogeological hazards are far from being solved.

Further development of the hydrogeological monitoring system is a crucial prerequisite for the timely identification and determination of a path forward for mitigating hazards threatening architectural monuments. To protect and preserve the objects of the Kyiv-Pechersk Lavra, it is important to introduce into practice the modern methods of monitoring, collection, and analysis of data on parameters of heritage objects integrated with predictive mathematical modeling, such as SHM – IoT (Structural Health Monitoring – Internet of Things) methodologies (Scuro et al., 2021; Soleymani et al., 2023). The collected information can become a basis for a rigorous risk management framework for the mitigating of hydrogeological hazards. Application of the SHM methods could become a topic of scientific-technical cooperation and exchange between Ukrainian and European experts, who have experience in application of modern sensors, information technologies, and analytical methods to preserve heritage sites and architectural monuments.

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Competing interest

The authors declare no competing interests.

Author contributions

The work was initiated and supervised by SS. The concept of the article was prepared by IC and DB. Material preparation and data analysis was performed by IC and TK. Figures were prepared by TK and IC. The manuscript was drafted by IC and DB, and was reviewed by TK and SS.

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Supplementary Materials

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