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Hydrogeological monitoring for landslide hazard mitigation: case study of the Near Caves Hill slope of Kyiv-Pechersk Lavra

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SUMMARY

The Near Caves Hill of the Kyiv-Pechersk Lavra is a zone of active development of hazardous engineering-geological processes caused by excessive soil mass over-saturation and the activation of landslides under the influence of natural and anthropogenic factors. Cave complexes are located within the sandy loam layer of the hill's soil mass in a landslide-prone zone. Long-term observations indicate that changes in hydrogeological conditions, caused by urbanisation since the second half of the 20th century, have led to fluctuations in groundwater levels and the development of soil over-saturation processes, which negatively affect the stability of the slope and the objects located within it. To establish the relationship between over-saturation and the activation of landslides, a comprehensive system of hydrogeological monitoring was implemented. The research methods included regular visual inspections, weekly measurements of groundwater levels in 20 observation wells, soil moisture monitoring, GIS mapping of moisture zones and the aquifer, as well as meteorological data analysis. According to the results of 35 years of monitoring, groundwater levels fluctuate between 0.9–3.2 m, with recharge occurring from atmospheric precipitation (59%), lateral inflow (22%), and leaks from water supply networks (19%). The retaining walls create a barrage effect, which causes over-saturation and reactivation of landslides. The obtained data made it possible to identify landslide risk zones and implement engineering protection measures, such as relief holes in the walls and a system of radial drains, which improved the stability of the Near Caves Hill.

Introduction

The soil mass of the Near Caves Hill of the Kyiv-Pechersk Lavra contains a unique complex of underground labyrinths of global historical and cultural value – the Near Caves, with a total length of 380 m. According to research (Kril et al., 2024), their condition is approaching an emergency state. The main factor that has led to the critical condition of the cave galleries is the over-saturation of the soil mass and the activation of landslide displacements caused by natural and anthropogenic factors.

The Near Caves are located within a sandy loam layer (N_1pt) on the southern slope of the Lavra ravine, within a landslide-prone zone. In the studies by M. Zakrevskyi (1868), data were presented on the development of landslide processes and the destruction of the cave complex. The last two landslides occurred due to leaks from water-supply networks in 1995 and 1998. To stabilize the landslide processes and preserve the caves, a system of engineering protection measures has been introduced at different times, including retaining walls and various types of drainage systems.

The condition of the cave complexes and the adjacent territory, as well as the organization of monitoring of time-variable parameters, have been studied at different times by the Institute of Geological Sciences of the NAS of Ukraine (1985–2010), the Research Institute of Monument Protection Studies (2005), the GeoProm Scientific and Production Enterprise (2005–2007, 2020), Geo-Eco-Consulting LLC (2008–2011), and by specialists I.A. Cherevko and V.O. Kutsyba from the Monitoring Department of the National Reserve “Kyiv-Pechersk Lavra”. Strengthening works were carried out by the Municipal Enterprise "Specialized Department of Landslide Prevention Underground Works" (ME “SDLPUW”) in 2017. It has been noted that the main reason for the deterioration of the caves' condition is excessive soil moisture against the background of disturbed hydrogeological conditions of the area, which are associated with the impact of urbanization processes since the second half of the 20th century.

Various aspects of the study, monitoring, and management of both natural and anthropogenic factors of landslide hazards and the deterioration of cave complexes have been highlighted in works (Toomey, 2009; Dabove et al., 2023; Topal & Kaya, 2024), which mostly concern cave sites located in rock formations. In the study (Domej et al., 2022), the static stability of the man-made Sabereebi Cave Monastery (Georgia) was assessed using elastoplastic finite element stability models with different levels of detail. Each model focused on specific geomechanical scenarios, such as classic slope failure due to overloading, deformation of architectural elements resulting from stress concentration, and material response to weathering. A similar model was created for the Lavra caves (Shults et al., 2019); however, it does not provide a clear understanding of the factors contributing to their deterioration. Hydrogeological monitoring studies have proven to be the most effective (Rybin et al., 2001; Skalsky et al., 2007; Rudenko et al., 2021; Cherevko et al., 2024).

The aim of the study is to establish a cause-and-effect relationship between soil mass over-saturation and the activation of landslide processes based on the results of hydrogeological monitoring, as well as to justify the role of monitoring as a key tool for preventing landslide hazard risks.

Methods

The study applied a complex of observational and mathematical methods, in particular:

– Regular visual surveys of the territory of the Near Caves Hill and the cave complex.

– Weekly observations of groundwater levels in the garden above the Near Caves using the WLT Meter Model 201 electric water level meter (Solinst, Canada).

– Investigation of moisture movement in the unsaturated soil zone at hydrophysical stations using the SM150T sensors (Delta-T Devices, Great Britain), with data collected by DL6 Data Loggers.

– Periodic (once every few weeks) measurements of the moisture content of the structural elements (walls and vaults) of the caves at specially equipped points: for walls composed of natural soil – using the SM150T sensor connected to the HH2 Moisture Meter (Delta-T Devices, Great Britain); for plastered, concrete, or wooden walls – using the Testo 606-2 sensor (Germany).

–Mapping of moisture zones using GIS tools.

–Mapping the distribution zones of the aquifer using GIS interpolation methods.

–Analysis of meteorological conditions and the formation of a database of temperature, precipitation, and other related parameters.

Results

The territory of the monastery garden above the Near Caves is equipped with 20 observation wells. According to the 35-year monitoring data, groundwater on the slopes of the Lavra ravine occurs at depths ranging from 0.9 to 3.2 m below the ground surface. The thickness of the aquifer varies from 1 to 5 m, and the amplitude of fluctuations is 1.2–3.4 m. In the upper part of the territory, the aquifer is permanent, while in the lower part it is temporary, forming on the clay surface during snowmelt and extended periods of precipitation and persisting for 6–8 months (Cherevko, Kril, & Bugai, 2024).

The formation of the groundwater aquifer occurs due to infiltration of atmospheric precipitation (59%), lateral inflow from the Upper Lavra area (22%), and leaks from water-supply networks (19%). Groundwater flows down the slope towards the caves as stream-like channels through depressions within the clay layers (Figure 1). Retaining walls at the foot of the hill on the southern and eastern sides act as a kind of barrier for the groundwater flow. The walls retain groundwater, creating a barrage effect, which leads to over-saturation of the soil mass and the discharge of the aquifer into the cave labyrinths located at depths of 6–8 m, as well as through the retaining walls via cracks and damaged weakened zones.

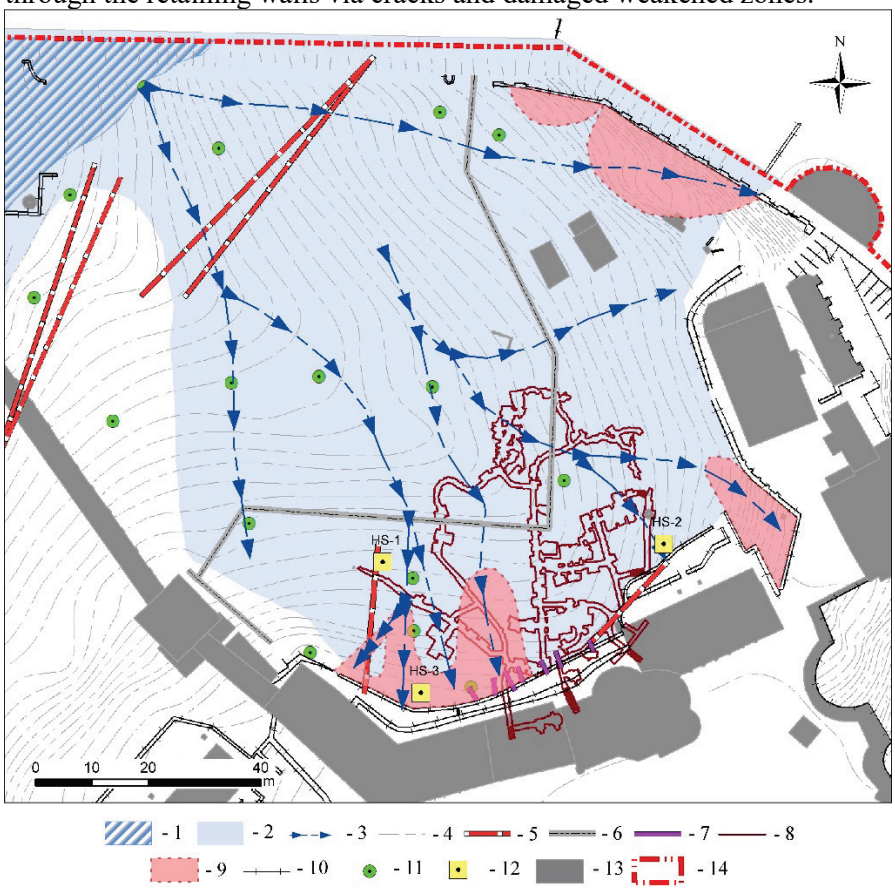

Figure 1 *Scheme of hydrogeological conditions, locations of accidents and engineering mitigation measures at the Near Caves site: 1 – zone of the permanent aquifer in Quaternary deposits, 2 – zone of the temporary aquifer (as on March, 2025), 3 – groundwater preferential flow path lines, 4 – ground surface isolines, 5 – horizontal drainage, 6 – surface storm water apron, 7 – drainage holes in the retaining walls,*

8 – cave galleries, 9 – landslide hazard area, 10 – retaining walls; 11 – monitoring wells, 12 – hydrophysical stations; 13 – buildings; 14 – boundary of Lavra.

As a result of significant over-saturation of the soil mass, landslide displacements are activated specifically along the retaining walls, which manifest as tension cracks on the ground surface and cracks with masonry displacement in the retaining walls. Based on mapping of the aquifer distribution zones (according to groundwater level observations) and geophysical surveys, areas of landslide development caused by persistent (long-term) over-saturation have been identified (see Figure 1).

To reduce the impact of the barrage effect on the condition of the caves and the soil mass, relief holes were installed in the retaining wall. Additionally, groundwater drainage was performed using non-destructive methods (radial drainage).

To determine the characteristics of moisture movement, including infiltration of atmospheric precipitation, hydrophysical observation stations (HS) were installed in June 2022 on the territory of the Near Caves Hill.

The relevance of this work is due to the recent development of hazardous geological processes in the Near Caves area of the Kyiv-Pechersk Lavra, such as excessive moisture, cracking and soil collapse within the caves, landslide processes on the slopes, among others. The primary cause of these processes is unfavorable changes in the hydrogeological regime of the study area.

The established hydrogeological monitoring system is designed to collect objective data and provide operational control over the hydrogeological and meteorological conditions of the study area, as well as to study the short-term (seasonal) and long-term (multi-year) dynamics of hydrogeological parameters (moisture content in slope soils, moisture content in cave walls, groundwater levels, etc.). Analysis of the monitoring data enables identification of key factors (meteorological and anthropogenic) negatively affecting the hydrogeological conditions of the study area, which is a necessary prerequisite for justifying measures aimed at protecting the caves and aboveground architectural monuments from adverse geological processes.

HS-1 and HS-2 are designed to record soil moisture measurements at depths ranging from 1.0 to 7.0 m in order to determine the mechanisms and possible pathways of water infiltration into the cave galleries. HS-3 is located within the influence zone of the retaining wall, which retains surface and subsurface flow, creating a damming effect that contributes to over-saturation of the soil mass and activation of landslide processes. It is also situated near a vineyard, which allows for testing the hypothesis regarding the role of vineyard rows and pits as conduits for surface water flow into the cave labyrinths. Sensors are installed in soils of varying lithological composition.

During the three-year period of sensor operation, the influence of atmospheric precipitation infiltration on soil over-saturation was recorded up to a depth of 2 m, depending on the soil type. There was almost no correlation between atmospheric precipitation infiltration and soil moisture at depths of 4 to 7 m. A significant impact of anthropogenic factors (irrigation) was also observed. Additionally, substantially higher moisture levels were recorded in disturbed soils (fill and landslide soils) – 36-56%, which exceeds the moisture content of undisturbed soils by 2 to 4 times.

Conclusions

The main factors contributing to the development of hazardous engineering-geological processes (flooding, erosion, landslides, etc.) within the Near Caves Hill are combinations of natural factors (infiltration of atmospheric precipitation, groundwater level rise, seismic impacts) and anthropogenic factors (construction of deep foundations, excessive irrigation).

Observations of groundwater levels make it possible to detect emergency leaks from water-supply networks and promptly take management decisions for their elimination, which is an important part of measures to prevent the development of landslide processes.

Hydrophysical observations showed that the soil moisture in disturbed masses (fill, landslide-affected, etc.), where the sensors are located, is significantly higher compared to soils in their natural undisturbed state. This indicates that such areas are more vulnerable to over-saturation and may become centers of landslide

activation. Thus, the results of hydrogeological monitoring make it possible to timely identify hazardous zones and predict the development of negative engineering-geological processes on the slopes.
Cartographic comparison of the outlines of underground groundwater flows with landslide zones revealed a clear spatial correlation. This confirms the key role of soil mass over-saturation in the development and activation of landslide processes on the slopes of the Near Caves Hill.
The implemented monitoring made it possible to identify the main factors of landslide hazard – the areas of soil mass over-saturation within the slope. This, in turn, allowed for the development and implementation of engineering protection measures, in particular, relief holes in the retaining walls and a system of radial drains.

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