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ASSESSMENT THE RISK OF DESTRUCTION THE CULTURAL LAYERS ON THE TERRITORY OF MEDIEVAL PECHERSK MONASTERY RELATED TO LANDSLIDE GENESIS

LIUBOV TUSTANOVSKA
Taras Shevchenko National University of Kyiv, Institute of Geology, 90 Vasylkivska, Kyiv, 03022, Ukraine,
ljume4@ukr.net
ORCID: 000-0003-0079-2258

VIKTOR NESTEROVSKYI
Taras Shevchenko National University of Kyiv, Institute of Geology, 90 Vasylkivska, Kyiv, 03022, Ukraine,
v.nesterovski@ukr.net
ORCID: 0000-0002-7065-8962

SERGIY TARANENKO
National Reserve "Kyiv-Pechersk Lavra", Lavrska, 9, Kyiv, 01015, Ukraine,
taransun@ukr.net
ORCID: 0000-0003-0590-9726

IRYNA CHEREVKO
National Reserve "Kyiv-Pechersk Lavra", Lavrska, 9, Kyiv, 01015, Ukraine,
ira071165@yahoo.com
ORCID: 0000-0001-7083-6119

OLENA MAKHOTA
National Reserve "Kyiv-Pechersk Lavra", Lavrska, 9, Kyiv, 01015, Ukraine,
makhota-olena@ukr.net
ORCID: 0000-0002-2742-4255

Abstract. In 2016, a modern Archaeological map of the territory of the Kyiv Pechersk Lavra National Preserve (NR KPL) was developed, serving as a foundation for conducting research aimed at the preservation of the diverse cultural layers of this unique complex, spanning the period from the 11th to the 19th centuries. The Preserve is situated on the distinctive Pechersk Hill whose formation is influenced by dynamic natural and man-made factors that adversely affect the feature's environment. Since the terrain acts as an indicator of the complex interaction of these processes, its detailed analysis provides an effective means for investigating the slope's evolution. The objective of this study is to construct digital models of the paleorelief integrated with the existing Archaeological Map of the NR KPL, and to establish a database for risk assessment within the excavation zones. A structural and morphometric analysis served as the principal methodological tool. Among the numerous results obtained, the most informative were the quantitative and qualitative characteristics of the residual relief (forecast) maps, and the differential maps between the summit and base surfaces (dynamic maps). These outputs enabled the reconstruction of the detailed evolution of the slopes, the identification of areas of active erosion, and the assessment of the potential risk zones at the archaeological and architectural sites, notably the Dormition Cathedral (K-80), the Church of the Saviour at Berestove (K-84), the Church of the Nativity of the Virgin Mary (K-59), and other features.

Keywords: cultural layer, Archaeological map, Kyiv-Pechersk Lavra, Pechersk Monastery, structural--morphometric analysis.

Introduction and problem statement

One of the main tasks of the National Reserve "Kyiv-Pechersk Lavra" is to protect cultural heritage sites. The Reserve is responsible for their maintenance, protection, preservation, and proper use. The Archaeology Research Department also conducts archaeological field studies, identifies locations in need of urgent rescue work, and organizes actions to prevent or mitigate damage. In recent years, such issues have become more frequent.

The Pechersk hills are located on the right bank of the Dnipro River. They are composed of rocks with various minerals from different geological periods. These rocks react differently to human activity and natural forces. As a result, slope processes develop differently in various areas.

The shape of the slopes on the right bank of the Dnipro River is formed by a ense system of gullies and ravines that are constantly changing. New gullies appear, and old ones expand due to both natural and human-made factors. In Kyiv, many gullies have been partially or fully filled in, reshaped, reinforced, or even built over – as is the case in our study area (Anishchenko and Borovyi 2006, p. 35). With the advancement of technology, the role of human impact continues to increase. The activation of external geological processes in urban areas is closely linked to human activity. This also affects cultural layers where archaeological sites are located.

The goal of our research is to study changes in natural and human-made systems within the Reserve and to define the quantitative and qualitative features of slope processes. This is important for predicting dangerous events in areas with archaeological and architectural objects.

Methods. For this research, we used traditional geological and geomorphological methods. The main data were obtained from observation wells and fieldwork within the Reserve. Spatial analysis methods were applied to process this data. To establish the link between landforms and tectonic processes, as well as between surface shapes and deep Earth structures, we applied structural morphometry. This method helps study landforms created at different times and by different geological processes – all of which are present at our study site. Changes in landforms were represented on specially created maps.

During the research, we placed the main architectural objects of the Reserve on a digital model of the current land surface. These include: Dormition Cathedral (K-80) in the Upper Lavra, Church of the Saviour at Berestove (K-84) in the northwest, Onuphrius Tower in the northeast part of Upper Lavra, and Church of the Nativity of the Virgin Mary (K-59) in the eastern part of Lower Lavra. The Archaeological Map was also used, with marked archaeological sites. In the following text, we will refer to these buildings by their index only.

Overall, the Reserve area is a complex, multi-layered heritage site. It includes elements from different historical periods (from the Eneolithic to modern times), with various functions – religious, domestic, industrial, military, and technical. Each holds unique historical and cultural value (Taranenko 2016, s. 56; Taranenko, Mysko and Zazhyhalov 2019, p. 16).

Research results and analysis

Archaeological content. The Archaeological map includes 301 sites, described using the following methods (Fig. 1):

Each site's shape (minimum shown size – 1.5 × 1.5 m) matches its real form in the field – trench, test pit, or excavation area.

Cultural layers from different time periods are marked with different colors:

Eeolithic (late IIIrd millennium BC) – dark brown

Early Iron Age (IVth-VIth century BC) – light brown

Kyivan Rus period (XIth-XIIIth century) – red

XIVth-XVIth century – blue

XVIIth-XVIIIth century – green

XIXth-XXth century – yellow

For multilayer sites, the color reflects the *earliest* period. If older artifacts appear in later cultural layers, they are marked with a small circle in the matching color placed on the main layer background.

Object numbering uses the last two digits of the year of excavation (e.g., 1979 = 79). If several sites were studied in the same year, an additional number after a dot shows the sequence (e.g., 2017 = 17.1, 17.2, etc.).

Sites with repeated research and complex stratigraphy are shown separately at a larger scale. This allows all identified features and structures from different periods to be clearly presented. These areas include the Dormition Cathedral, the Church of the Saviour at Berestove, the Old Rus refectory, and the Near, Far, and Varangian caves. (Taranenko 2016).

The Archaeological map was aligned with a topographic plan at a 1 : 500 scale, which served as the base for structural and morphometric studies. In total, 18 maps were created, including: five maps of valley orders, five maps of watershed lines, five maps of base surfaces, five maps of top surfaces, five maps of residual relief, and three maps of top-to-base surface differences. Each type of map has its own focus and corresponds to a specific historical period. All maps are linked to the Archaeological map and serve as individual information sources for the research.

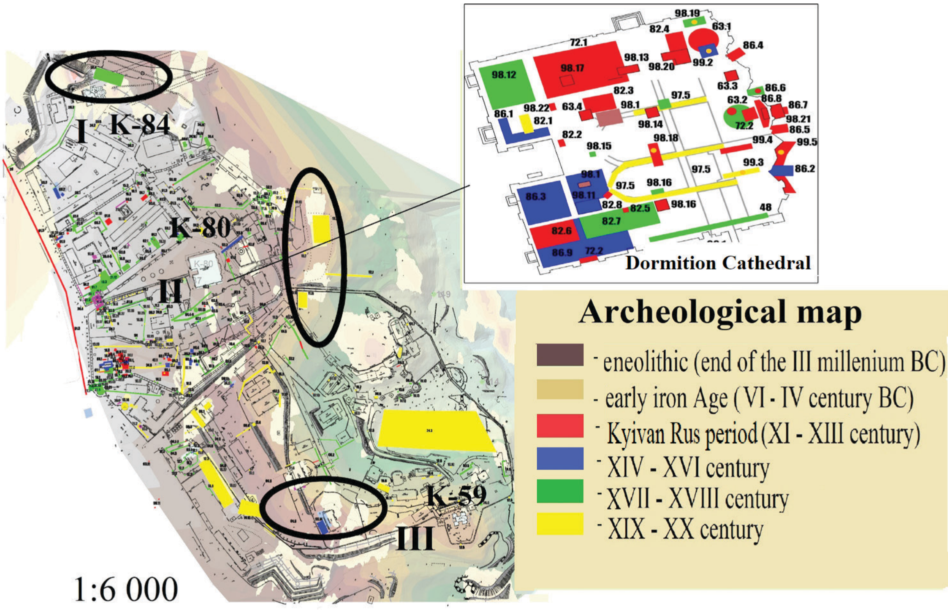

Fig. 1. Archaeological and architectural sites and areas of potential hazards (hazard forecast map and Archaeological map of the NR KPL [fragment of the plane of the Dormition Cathedral])

When comparing the locations of archaeological excavations with the risk forecast data, a clear correlation is observed between the development of hazardous slope processes and the positions of excavation sites (Fig. 1).

In this publication, we will focus only on the main historical and architectural landmarks of the Reserve, which are significantly influenced by exogenous forces.

Object K-84 – the Church of the Savior at Berestove. It is located in the hazardous Zone I. This landmark includes remains of a monumental structure from the second half of the XIth century to the first half of the XIIth century. It was discovered through comprehensive research led by Professor P.P. Pokryshkin between 1909 and 1914. The church is a large six-column cross-domed structure, measuring 20×30 m. The masonry was made of plinths – wide, flat, fired tile-like bricks. The most commonly used plinths were 35 × 30 × 4-4.5 cm. In 1947, I.M. Samoylovsky conducted search work in the area of this landmark in an attempt to find the burial site of the Kyiv Prince Yuri Dolgoruky. In 1989-1990, the Architectural and Archaeological Expedition of the Institute of Archaeology of the National Academy of Sciences of Ukraine (led by V.O. Kharlamov) carried out field studies on the site of the Church of the Savior at Berestovo, during which two slate sarcophagi were found outside the church, and another previously known one (discovered by P.P. Pokryshkin in 1914) was re-examined. As a result of archaeological excavations in 2003 (led by H.Y. Ivakin), a significant portion of the interior space of the Church of the Savior at Berestovo was studied, providing clarification on the overall stratigraphic situation of the landmark and the nature of repair and restoration work from the early 20th century. In 2018-2019, archaeological research was carried out by the Scientific Research Sector of Archaeology at NKPIKZ (led by S.P. Taranenko) and the Architectural and Archaeological Expedition of the IA NAS of Ukraine (led by V.H. Ivakin). During the investigation of an area over 700 m², cultural layers and objects from the early Iron Age, Kievan Rus, Lithuanian, early modern, and modern times were recorded. Among the studied objects, it is important to highlight a structure from the Chernolis culture of the IXth century and a settlement from the late stage of the Chernolis culture (IXth century BC), named Pecherske-1. Over 300 finds were discovered, most of which were fragments of hand-made ceramic vessels. The necropolis of the Church of the Savior at Berestovo, dating from the XIIth to the XIXth century, is one of the oldest parish cemeteries in Kyiv. The prolonged active use of the cemetery in a limited area led to the placement of graves in multiple layers. During the archaeological research of 2018-2019, 431 burials of varying preservation were recorded. Among them, particular attention is given to complexes with various burial structures. Important objects for the history of Ukraine include the studied finds from the Rus-Lithuanian period and pre-modern times: a furnace from the XVth-XVIth centuries, a structure from the XVIIth century, and a fortification rampart from the XVIIth-XVIIIth centuries (Taranenko 2021).

Object K-80 – the Dormition Cathedral. It is located in a potentially dangerous Zone II for landslide development (Fig. 1). After the destruction of the cathedral in 1941, the study of the monument's remains continued intermittently throughout the second half of the last century, with a reduced archaeological component. In the 1950-s-60-s, the work mainly involved the systematic dismantling of construction debris, with careful documentation of significant architectural details of the cathedral (M. V. Kholostenko). The role of the archaeological method at this stage was relatively minor and mainly consisted of setting up individual exploratory trenches, surveying the semi-destroyed vaults of the XVIIth-XVIIIth centuries damaged by the explosion, and examining accidentally discovered earth burials from the Dormition necropolis, among other tasks. Much more significant archaeological work was carried out by the Architectural and Archaeological Expedition of the Institute of Archaeology of the NAS of Ukraine (led by V. Kharlamov) during the 1982 and 1986 seasons. The main objective of this work was to gather necessary information for the project to reconstruct the Dormition Cathedral, which was then being developed. The most recent research on the Dormition Cathedral (1998-1999, led by H. Y. Ivakin) was conducted in the context of the beginning of the cathedral's restoration and was primarily focused on conservation and rescue efforts. Nevertheless, even under these conditions, a number of new archaeological discoveries were made within the „footprint" of the monument, which are significant for understanding both the history of the Dormition Cathedral itself (two groups of burials in slate sarcophagi, the burial of the well-known XVIIIth – century church figure P. Tobolsky, and others) and the historical development of the monastery territory in general (remains of a Tripolye settlement from the III-rd millennium BC and cultural layers from the Scythian period, I-st millennium BC). (Taranenko and Balakin, 2017, s. 55). The Dormition Cathedral is located to the west of the current landslide development area, but it is evident that if the erosion zone expands, the danger will eventually reach the foundation of this structure.

Object K-59 – Church of the Nativity of the Virgin Mary. It is located in a potentially hazardous Zone III. Particularly significant here are the underground structures – the caves. The Lavra caves are monuments of underground architecture, archaeology, history, and culture. Today, they form a complex system of interconnected underground passages that link cave rooms together. The Lavra caves are partially man-made. They are situated at a depth of 5 to 15 m below the surface, within a layer of weakly cemented loess-like clays.

There are two cave complexes – the Near and Far caves, with a total length of over 800 meters. The names „Near" and „Far" refer to their distance from the main monastery church – the Dormition Cathedral. The caves are located on two adjacent hills, between which runs a deep ravine where the famous wells of Saints Antony and Theodosius are located.

The Far caves were built as a completely separate complex. Their historical study is complicated by the fact that no systematic archaeological research has been conducted there. The oldest part of the Far caves is considered to be the location of the Varangian caves. It is these caves that are associated with the founding of the monastery itself.

Currently, the Far caves house three underground churches: the Annunciation of the Blessed Virgin Mary, the Nativity of Christ, and Saint Theodosius (Lytvynenko 2024, p. 57). Archaeological studies in the Far caves were conducted in 1968 (Yura 1968) and 1999 (Strykhar 1999), and in the Varangian caves – in 1937 (Samoylovsky 1967) and 1998 (Stryhar 1998) (Taranenko, Mysko and Zazhyhalov 2019, p. 16).

Structural and Morphometric Analysis of Base Surface Maps. Analysis of the base surface maps made it possible to trace the evolution of the Pechersk slope over a period of about 1500 years. For a complete reconstruction of the genesis of the slopes of the Pechersk Lavra territory, morphometric maps of different orders and ages were created. Based on these maps, an analysis of the elevation of the areas of the aforementioned buildings was conducted: K-84 has an absolute elevation of 189.9 m (excluding the height of the fortification ramparts); K-80 – 187 m; K-59 – 168 m. These elevations will serve as reference points for further calculations of the relief dynamics (Kondratyuk 2007, p. 25).

The interpretation of the results of the constructed maps was carried out from the highest order to the lowest. The highest order corresponds to the ancient relief,

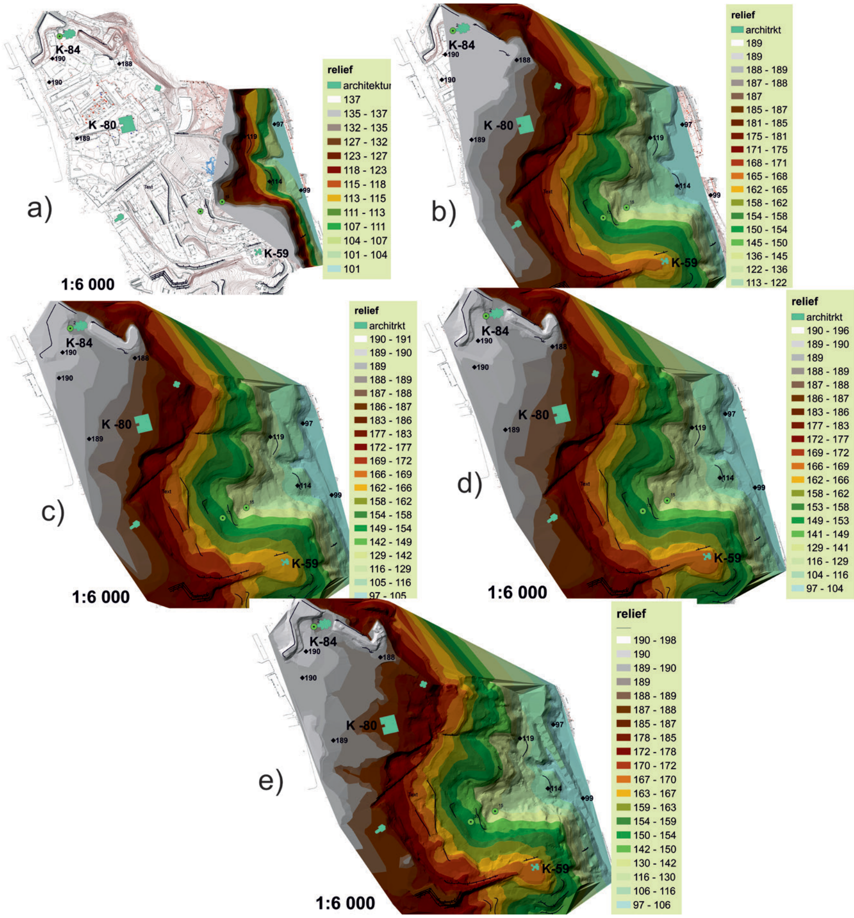

Fig. 2. Evolution of the paleo-relief of the slope of the National Reserve „Kyiv-Pechersk Lavra" [base surface maps: a) 5th order; b) 4th order; c) 3-rd order; d) 2-nd order; e) 1-st order (modern relief)]

and the lowest (first order) corresponds to the modern relief. The oldest (around 1500 years ago) is the 5th-order base surface map. It covers a small area of the hill with a maximum relative elevation of 137 m and is part of the Pechersk slope (Fig. 2a).

During its development, the slopes evolved, and a network of ravines formed, which is reflected on the 4th-order base surface map (Fig. 2b). This pattern is characteristic of the paleo-relief of the entire study area. The maximum relative elevations are the same as the current ones – 189 m, while the minimum elevations are 108 m, indicating the distance of the Dnieper Valley from its current state.

The morphological appearance of the slope at this stage, compared to its current position, had a greater steepness at the foot of the slope, particularly noticeable in the area of the fortifications of the Citadel complex and the K-59 church. It is likely that, at that time, the erosion of the Lavrsky Ravine was actively developing, which is now filled and built up (Fig. 2b).

The further development of the slopes is reflected on the 3rd-order base surface map. On this map, the minimum elevation values decrease, likely associated with the development of the equilibrium profile of the Dnieper Valley to 97 m. Maximum elevations reach up to one meter, suggesting the likelihood of ancient movements in the crystalline bedrock. As the course of the Dnieper River has been reconstructed, the erosion processes of the ravine system have become more active. This is well illustrated on the map with the compression of isobases and the color correlation of spatial indicators (elevations), as well as in the deepening of the Lavrsky Ravine valley (Fig. 2c).

Analyzing the 2nd-order base surface map, which demonstrates the formation of slopes several hundred years ago, a slight change in spatial indicators is observed (Fig. 2d). In the pre-modern period, the slopes of the plateau (where the Dormition Cathedral is located) were 1.5 m higher than their current position, ranging from 186 to 188 m. In two directions, northeast and east, significant erosional incisions are observed, directed toward the Dnieper River valley. The hill where the K-59 church is located maintains its elevation and has current elevation values of 166-169 m. However, erosional forms are recorded on the eastern slopes of the hill, which are closely approaching the church's foundation. The K-59 church stands on waterlogged moraine deposits, which are located at an elevation of 160 m. The water in these deposits has an infiltration character and exhibits seasonal variability.

The slopes near the K-84 church are also characterized by significant steepness and dissection. The 1st-order base surface map corresponds to the modern relief, highlighting all elements of erosional forms and their consequences (Fig. 2e).

Thus, the analysis of the obtained base surface maps clearly captures the evolutionary changes of the paleo-relief of the Kyiv-Pechersk Lavra National Reserve (NR KPL). These changes led to shifts in elevation indicators within the built-up areas relative to the erosion base of the Dnieper Valley, significantly altering the morphological features of the Pechersk Hill.

The analysis of the summit surface maps showed that, morphologically, they do not significantly differ from the base surfaces. Therefore, the obtained summit surface maps were mainly used to construct maps of differences between the summit and base surfaces of the same order, which were necessary for further construction and analysis.

Morphostructural analysis of the maps of differences in top-base surfaces and residual relief. The maps of differences in top-base surfaces illustrate the relationship between the nature of neotectonic movements and their orientation. To study the dynamics of the slope within the Pechersk horst, three age-differentiated maps of differences in top-base surfaces of the 4-th, 3-rd, and 2-nd orders were created.

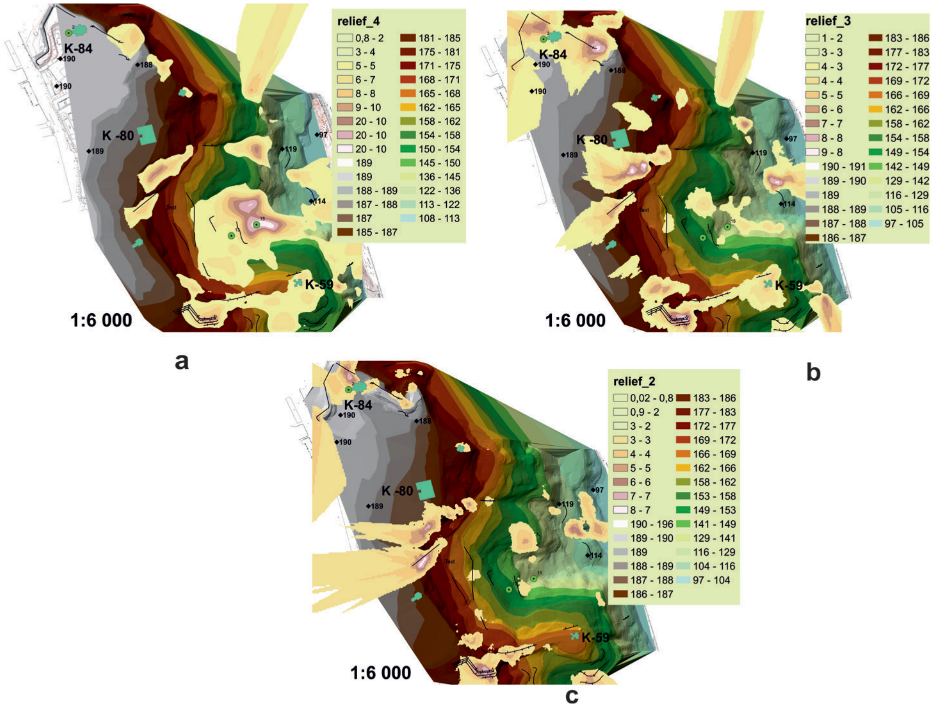

Fig. 3. Dynamics of paleoslopes within the Kyiv-Pechersk Lavra Reserve (difference maps of summit-basis surfaces: a) 4th order; b) 3rd order; c) 2nd order)

Based on the obtained results, the movement of the earth's surface, along with denudation and accumulation processes, was tracked over a short period of time (Tustanovska 2024, p. 36).

For an effective analysis, the difference maps were superimposed on the paleo-relief maps of the corresponding order base surfaces. This made it possible to determine the dynamic characteristics at various stages of slope formation, starting from the earliest (4-th-order top-base surface difference map). At this stage, local areas with amplitudes of 5-10 m were recorded, located along all erosion zones. It should be noted that, alongside the formation of the slope, the entire erosion system was developing. The largest amplitudes of 10-20 m were recorded in the area at the head of the Lavrsky Ravine. This indicates the active development of linear erosion (Fig. 3a). As a result, the right bank of the ravine cuts into the slopes at elevations of 136-168 m, thus deepening it. The same trend is observed on its left bank at elevations of 168-187 m, with an incision of up to 10 m.

Northward along the slope, at the same elevations behind the Citadel complex, near the Near Caves, another small erosion area begins to form. In interaction with linear erosion, sheet wash develops, affecting areas with low indicators of up to

5 m. The largest number of such areas is concentrated at the foot of the southern and southeastern slopes of the Lower Lavra, near the Far Caves.

At altitudes of 181-189 m, local denudation processes are widely observed. According to borehole profiles at these elevations, loess-like clays and sandy loams cover the area as a continuous blanket. The base of the loess consists of dense, fine-powdery loess-like clays of pale-yellow and yellowish-gray colors, with a columnar texture and carbonate streaks. These deposits are locally spread with varying thicknesses, ranging from 0.7 to 4.8 m. The upper layer of clay is represented by loess-like sandy loams, which are quite porous with carbonate inclusions. The absolute height of the loess layer ranges from 176-186 m on the plateau and 140-150 meters on the slopes, underlain by moraine deposits. The total exposed thickness of the loess ranges from 1.2 to 7.8 m, with plastic and flow-plastic interlayers (Arhypenko 2017, p. 17).

The moraine is represented by yellowish-red to brown silty clays with layers of sand, containing gravel and pebbles of crystalline rocks. Their thickness is variable, ranging from 2 to 12 m, with firm and plastic, flow-plastic interlayers at absolute elevations of 168-174 m. The moraine deposits lie on the undivided Neogene-Eopleistocene (N_2E) layer of brown and variegated clays (Arhypenko 2017, p. 17; Cherevko 2017, p. 40).

Overall, the map of the difference in the fourth-order peak-basis surface has reconstructed the denudation-erosion activity of the area in the past. During this period, the greatest slope dynamics were observed in the Lavra Ravine, indicating its active development. It should be noted that slope deformation was also evident on the slopes of the Lower Lavra.

Based on the analysis of the third-order difference map, the pre-modern dynamics of the slopes were reconstructed. Compared to previous data, the nature of the erosion-denudation processes at this time changes: the slope dynamics slow down, and the area of local erosion zones decreases. The regression of the left bank of the Lavra Ravine continues, with further development of the equilibrium profile of the main channel. At this stage, unlike the previous one, the areas of denudation cuts increase. These areas are primarily located on the loess-like clays of the plateau, which lie at elevations of 172-189 m of the paleorelief and have significant thickness. Additionally, large areas of denudation material (up to 9 m) are recorded near the Church of the Savior at Berestovo, around the fortification mounds of the Upper Lavra, and to the south – the Lower Lavra. All these areas in the territory of the Reserve occupy the highest positions in the paleorelief. Alongside denudation, linear erosion develops, producing the equilibrium profile of the Lavra Ravine, with the eroded material accumulating at its mouth, which is later carried towards the Near and Far Caves (Fig. 3b).

At this stage, both in-plane scour and linear erosion are recorded. The slopes of the plateau are represented by loess deposits with carbonate content, which lie unevenly on waterlogged moraine and are subject to sufosic processes. This affects the stability of the slopes. It is the elongated appearance of the coloured areas along the slopes that were recorded by the difference maps that indicate the processes of suphosic transport (the area of the Dormition Cathedral).

The analysis of the second-order difference map of the peak-basis surface, which characterizes the pre-modern state of the area (Fig. 3c), showed that during this period, the dynamic activity of slope processes slowed down. This is evidenced by the reduction in the height of erosion indicators from 9 to 3 m and a decrease in the area of erosion zones. However, erosion processes continue to develop on the left side of the Lavra Ravine and in the area of the Near Caves. In contrast to the left side, the right slope of the ravine is gentler, and the eroded material accumulates on the slopes in the form of small terraces. These features are typical of prolonged surface denudation.

To the north of the Reserve, in the area of the fortification mounds, slope dynamics intensify, especially towards the Holodomor Memorial. Currently, products of both ancient and modern landslide processes are recorded in this direction. Erosion and denudation processes are also developing in the southern part of the Reserve (Lower Lavra). The slopes of the hill where the K-59 church is located are being leveled by surface wash (up to 3 meters). Since these slopes are composed of porous loess-like clays with columnar separation, resting on moraine deposits, landslide processes are accelerating in these conditions. Field studies confirmed the presence of elements of ancient landslides, overlaid with modern bodies in the form of terraces with “drunken forest”.

Thus, the analysis of the obtained results from the difference maps of the peak-basis surfaces has made it possible to model the age-specific dynamics of the slopes in the territory of the Kyiv-Pechersk Lavra National Reserve step by step. It has allowed for the identification of local areas with both active and slowed-down erosion and denudation.

Analysis of Residual Relief Maps. The most informative maps in terms of analyzing the potential development of hazardous geological processes and predicting them are the residual relief maps. These maps record the volume of rock that may be removed in the future by denudation processes under similar geological and physico-geographical conditions. Each base surface is characterized by its own residual relief values. The higher the order of the base surface, the greater the volume of rock that transitions into residual forms. The results of evaluating hazardous processes are shown on the residual relief maps in the form of multi-colored patches, representing the quantitative parameters of the residual relief thickness (in meters) (Shevchuk et al. 2020, p. 10; Ivanik et al. 2019, p. 3).

During the research, four residual relief maps were constructed and analyzed, providing a predictive assessment of denudation processes. The quantitative characteristics indicate the sequential movement of soil masses along the slopes of the paleorelief and assess the degree of potentially hazardous erosion zones. According to the fourth-order residual relief map, the movement of masses with a residual

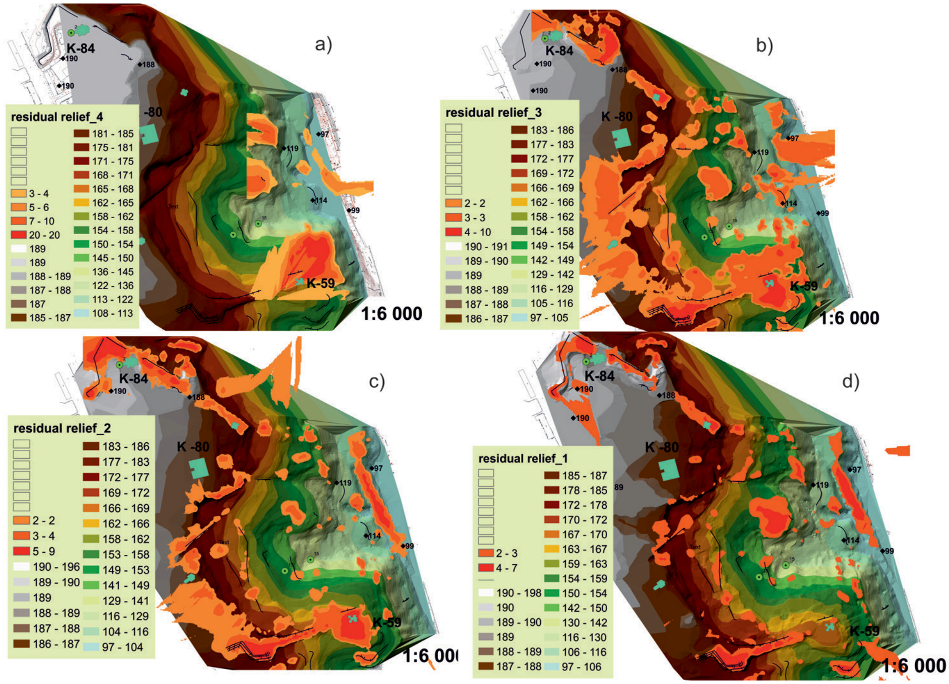

Fig. 4. Forecast maps of slope hazard assessment in the Kyiv-Pechersk Lavra Reserve (residual relief maps: a) 4th order; b) 3rd order; c) 2nd order; d) 1st order)

relief thickness of up to 20 m is predicted on both the right and left slopes of the Lavra Ravine. The eroded material accumulates at the foot of the ravine and is then carried downstream. Based on the quantitative parameters, the most hazardous areas have been identified, including the slopes of the hill near the K-59 church (up to 20 m) and the Citadel complex (up to 10 m), while the lowest thickness (up to 5 m) is recorded in the area of the Near Caves (Fig. 4a).

The following map of the residual relief for the 3-rd order illustrates a lower thickness of the eroded material (up to 10 m), compared to the previous one (Fig. 4b). This indicates continuous material removal influenced by the climatic conditions of the time. At this stage, the greatest denudation was recorded on the slopes of the hill where the K-59 church is located. Since the hill has the shape of an elongated cuesta, its slopes are complicated by a specific microrelief resulting from material erosion. The greatest concentration of these features is found on the slope in the Lavrsky Ravine. A smaller residual relief thickness, up to 3 m, is observed near the Citadel complex. The next dangerous slopes, where the residual relief has significant thickness, are those of the hill near the K-84 church and the fortification mounds, where the thickness reaches up to 10 m. Since the northern slopes directly descend to the Dnieper River bed, their erosive activity is continuous. Field studies in this area have recorded ancient landslides, now covered with vegetation, which have softened forms. The plateau of the Reserve has the smallest residual relief thickness, up to 3 m, and is observed only at elevations of 166-188 m. The plateau features flat watershed areas with a small slope, and no residual relief is recorded at elevations of 190 m. This indicates the stability of the slope deposits and the absence of anthropogenic pressure. All recorded fragments of the residual relief on the 3rd order map represent areas likely to be destroyed in the next stage of slope development, i.e., in the present day.

The results of the 2-nd-order residual relief map reflect the current state of slope transformation (Fig. 4c). All areas of residual relief maintain their previous positions, but their thickness has decreased, indicating ongoing denudation of these areas. On the hills where the K-59, K-84, and K-80 objects are located, the thickness has decreased from 10 m to 5-9 m compared to previous data. Similar characteristics are observed in the areas of the Citadel complex, the Near Caves, and at the very top of the hill (K-59). Within these areas, field studies have mapped a number of ancient landslides, the elements of which are mainly concentrated along the right slope of the Lavrsky Ravine, which is now fully equipped with retaining walls.

The deterioration zone within the Dormition Cathedral is decreasing, which indicates the use of protective equipment. In the Upper Lavra, within the K-84 church and fortification mounds, slope processes are actively developing. This is evidenced by the significant thickness of the residual relief (5-9 m) and field observations.

The 2-nd-order residual relief map highlights hazardous areas of the current environment. It is through this map that the validity of the obtained results can be tested against contemporary events.

The results of the most recent first-order residual relief map provide a forecast of hazard zones within the Reserve (Fig. 4d). On most slopes, both the size of the affected areas and the volume of removed material have decreased compared to earlier data. For example, in the area around structure K-59, this suggests that anti-landslide measures, such as retaining walls, improved drainage systems, and slope reinforcement, have had a positive effect.

However, new zones with a residual relief thickness of up to 7 m have appeared in the Lower Lavra. They are most likely to be demolished by plane wash or suffosion, depending on the physical properties of the soil. This is especially critical near the Dormition Cathedral, in the direction of the Dnipro Valley (Nesterovskyi, et al. 2023, p. 3).

Due to recent construction in the Upper Lavra near the Onufriyivska Tower, landslide activity has been observed. Forecast data show erosion areas with a thickness of up to 7 meters, which could significantly alter the slope’s shape and negatively affect nearby architectural monuments and archaeological sites.

During field research within the area of the fortification walls, both modern and ancient landslide features were observed. Despite ongoing efforts to mitigate gravity-related processes, the height of the walls continues to decrease over time. Slope processes are especially active in the direction of the Dnipro Valley.

This issue affects an important object, K-84, which is located between two walls on a steep slope of the plateau (190 meters above sea level). The slope consists of thick loess-like loams, which exhibit clear signs of rapid erosion and instability.

Although drainage systems have been implemented, suffosion processes (the washing out of fine particles by underground water) are still active in this area. As a result, sinkholes and surface collapses have begun to appear, and these are recorded on the hazard forecast map. In spring 2017, a suffosion event occurred on the southern slope of the Spaska Bastion wall. It caused a flow of pulp material down to the area in front of the Church of the Saviour at Berestove (K-84), near the northern façade of the monument and along a runoff channel on the inner part of the southern slope (Arhypenko 2017, p. 15).

When analyzing the hazard forecast map, special attention should be given to the hill where object K-59 is located. This hill has the shape of a remnant (erosion-resistant formation) and is surrounded on three sides by erosion slopes and newly formed gullies. These processes are gradually reducing the land area near the foundation of the architectural complex. According to the research and forecast, the situation on some parts of the slopes may become more complicated in the future.

It is important to study the first-order residual relief map, which shows forecasted danger zones within the Kyiv-Pechersk Lavra Reserve. The areas of removed soil material, described earlier, point to ongoing slope movement.

Regular monitoring is needed in risk zones where architectural monuments and archaeological excavations are located. Special attention should be given to areas with a thick layer of residual relief. These include the Upper and Lower Caves, the Citadel complex, Onufriyivska Tower, and the northern and southern fortification walls. This applies not only to the mentioned monuments but to the entire territory of the Reserve.

Conclusions

To study the relief of the Pechersk Hills, a set of methods was employed, with the primary approach being structural and morphometric analysis. This method was crucial in reconstructing the evolution of the ancient landscape and understanding how erosion and denudation processes have transported material along the slopes of the Kyiv-Pechersk Lavra Reserve.

The main causes of slope instability within the Reserve were identified as follows:

Features of the soil and rock formations near the river, which have undergone repeated changes to their erosion base.

Geological structure of the slopes, composed of soft materials like loess-like loams and moraine, which are highly susceptible to erosion.

Human activity, including construction practices that do not adhere to technical regulations within protected areas.

Several maps were created to illustrate the various factors affecting the shape of the slopes. These maps include the effects of water and gravity-related processes, such as ancient and modern landslides, particularly on the slopes of Lavra Ravine, the northern slopes of Upper Lavra, and in proximity to the cave systems.

Underground water flows cause suffosion (the washing out of fine particles), leading to surface subsidence on the plateau. Human activities across the Reserve exacerbate natural processes, altering the landscape. Illegal construction and slope leveling further reduce slope stability, which is especially evident on the slope from the Dormition Cathedral down to the Dnipro River.

According to morphostructural analysis, about 30 unstable, landslide-prone areas were identified within the Reserve. Approximately 20 of these areas are particularly dangerous for architectural complexes and archaeological sites.

Based on the residual relief maps, a forecast of landslide risk was developed, highlighting local areas that may be prone to dangerous situations. Each map, from older formations to the present-day surface, offers a clear representation of places that have been or could be affected by erosion and denudation. This is especially critical for key monuments such as the Dormition Cathedral (K-80), the Church of the Saviour at Berestove (K-84), and the Church of the Nativity of the Virgin Mary (K-59), all of which lie within potential danger zones.

This residual relief model can be instrumental in preventing possible emergencies within the Reserve.

An Archaeological map was also created. Besides its scientific significance, this map has practical applications, such as supporting historical and architectural reconstructions of different periods of the Kyiv-Pechersk Lavra, aiding in the presentation and restoration of specific objects, supporting tourist excursions, and helping to protect heritage sites.

Recommendations

The following actions are recommended as first steps to mitigate danger:

Drainage of Underground and Surface Water: It is essential to update the drainage systems on the slopes, incorporating new data on contact zones between different soil and rock layers where mass movement occurs.

Reinforcement of Slope Stability Using Modern Technologies: Apply modern techniques to enhance slope stability and prevent landslides. These technologies may include slope reinforcement, soil stabilization, and geotechnical interventions.

Repair and Replacement of Water and Utility Networks: Conduct a technical inspection of existing systems, followed by repair or full replacement, to prevent leaks and reduce soil moisture, which can exacerbate erosion and landslide risks.

Upgrading the Monitoring System with Modern Tools: Implement modern monitoring methods, such as sensors, satellite monitoring, and automated data systems, for faster and more accurate detection of environmental changes, allowing for quicker responses to potential hazards.

These recommendations were presented at the 22nd International Scientific Conference *Church – Science – Society: Issues of Interaction*, held on May 23-24, 2024. During the presentation, maps were shown that focus on protecting the ecological state of the Reserve, especially archaeological and architectural monuments. They also included risk assessments of slope hazards and steps to prevent them.

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