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Identification of landslide hazard boundaries of the Dnipro slope near Mykilska Brama, Kyiv

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Визначення зсувонебезпечних меж дніпровського схилу біля Микільської брами, Київ

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Ключові слова: інженерно-геологічні умови, межі зсувної небезпеки, коефіцієнт стійкості схилу, надмірне зволоження, метод Янбу, інженерний захист, дніпровські схили Києва.

For the first time, the landslide hazard boundaries for the Dnipro slopes near Mykilska Brama have been scientifically substantiated and established, both for current and forecast conditions, based on the position of the slip surface. The study was conducted using a risk analysis of landslide activation, considering additional soil moisture as a result of the impact of anomalous meteorological and technogenic factors. The position of the slip surfaces was supported by the normative safety factor. Their delineation was carried out based on mathematical modeling for three profiles on the slope under natural physical and mechanical properties and in the forecasted (saturated) state. The calculations were performed using the RocScience Slide 6 software package, employing the Janbu method for a circular cylindrical slip surface. The engineering-geological conditions of this slope are characterized as complex due to the presence of a layer of subsiding loess soils and slope angles ranging from 20° to 43°. Field observations recorded markers of erosion-gravitational processes, including the “drunken forest” and tension cracks. The main factor for the loss of equilibrium of the soils on the slope is overmoisturization, which may result from anomalous rainfall or the influx of technogenic water into the soils from water supply network leaks. According to calculations of the slope safety factor in the forecasted state, in this case, with soil overmoisturization, a decrease of 10.4–22.4 % was determined compared to the actual condition. The landslide hazard boundary, considering the impact of additional soil overmoisturization and the corresponding decrease in soil strength properties, shifted by 30 meters in the middle section towards the edge of the slope. The methodology presented in the studies for determining landslide hazard boundaries serves as a practical tool for establishing such boundaries along the entire length of the Dnipro slope in Kyiv. Identifying landslide hazards in two states allows for the differentiation of risk levels associated with the loss of equilibrium of the slope’s soil mass and material losses due to the activation of displacements.

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1. Introduction

Urbanization processes and the development of construction technologies necessitate the use of areas with complex engineering-geological (geotechnical) conditions. In large cities, these include areas affected by landslides, flooding, subsidence, waterlogging, etc. In Kyiv, 18.9 % of the total city area consists of floodplain territories, 5% are landslide-hazardous or landslide-affected areas, 6.2 % are areas with a high groundwater level, and 6.6 % are areas with soils exhibiting subsiding properties (General..., 2024). Among them, the most attractive areas for construction investments are the slopes.

Designing structures on slopes requires a series of steps, including preliminary slope stability calculations, determination of safety factor values, justification of landslide prevention measures for the specific case, development of construction techniques for working on the slope, etc. (Demchyshyn, 1992; Bases..., 2009; Engineering..., 2017; Planning..., 2019).

A lot of researches focus on identifying the shapes of potential landslides at large scales (Ugenti et al., 2025) or creating small-scale maps that highlight areas with a high risk of landslide hazards (Jaedicke et al., 2014; Dahal B., Dahal R., 2017; Shekhunova et al., 2022; Yakovlev et al., 2024; Global..., 2024). For example, landslide hazard mapping based on expert and statistical models conducted for cities in Europe has proven to be a fundamental tool for disaster management, utilizing a ranking of areas where mitigation measures might be most effective (Jaedicke et al., 2014). The parameters considered include susceptibility factors (such as slope angle, lithology, soil moisture, vegetation cover, and other factors when available) and triggering factors (such as extreme precipitation and seismicity). Also, thematic maps representing various factors associated with landslide activity in the Higher Himalayas of Nepal were generated using field data and GIS techniques (Dahal B., Dahal R., 2017). However, when planning urban development and designing construction projects, it is more significant for architects, investors, and builders to have approved boundaries of landslide-prone zones, rather than the contours of individual landslides.

In such works, it is essential to consider the landslide hazard zoning schemes and landslide prevention measures. For the territory of Kyiv, these schemes were developed by Kyivproekt, Specialized Management of Landslide Prevention Underground Works (SMLPUW), and the Institute of Geological Sciences. They were created while taking into account geomorphological conditions, hydrogeological conditions, geological structure, and other factors. The purpose of the "Master Scheme of Landslide Prevention Measures" developed by "Kyivproekt" in 1983 was a regional forecast of landslide processes in Kyiv using analogy methods. To achieve this, 77 existing landslides in Kyiv were described based on data from the Kyiv Comprehensive Hydrogeological and Engineering-Geological Part "Pivnichukrgeologia" and "Kyivproekt", with their classification provided. On the SMLPUW map, landslide-hazard areas are marked along the edges of the slope terraces (Scheme..., 2020). In 2001, the "Map-Scheme of Landslide Processes in Kyiv, Highlighting the Most Hazardous Areas" was compiled by the Department of Engineering Geology of the Institute of Geophysics of the NAS of Ukraine (Demchyshyn et al., 2001) commissioned by "Kyivproekt".

However, given the changes in climatic and meteorological conditions, such schemes should be developed based on a risk analysis of the impact of anomalous meteorological conditions, changes in hydrogeological conditions. They should also be refined to account for the influence of emergency situations in water supply networks. Additionally, the impact of new construction must be considered not only on slope stability but also on existing buildings, particularly those of historical and cultural significance. In this case, the landslide hazard boundary, established by the safety factor representing the sliding surface, would determine the risk of a hazardous event occurring under the corresponding calculation factors. Considering the class of structures on the slope, whether built or under design, each of the defined boundaries may indirectly indicate the magnitude of material losses during gravitational shifts, or the amount of capital required to maintain the slope in a state of equilibrium and ensure the stable operation of the buildings. Considering such factors is possible using mathematical modeling methods and probabilistic approaches to determine slope stability (Bases..., 2009; Duncan et al., 2014; Khan, Wang, 2020; Shekhunova et al., 2020; Sampa, Schorr, 2024).

Stability calculations for the Dnipro slopes in the central part of Kyiv were conducted both under natural conditions and considering the impact of existing buildings during the construction of new buildings (Shumynsky et al., 2018a, b). The calculations, performed using H.M. Shakhuniants' method and an analysis of the stress-strain state, revealed a significant decrease in the slope safety factor when accounting for the weight of structures and complete soil saturation. This saturation may occur due to anomalous atmospheric precipitation, snowmelt, and full soil moistening.

Calculations performed using the Plaxis software application for modeling of the central part of the Dnipro slopes identified areas of potential landslides on total displacement contours and plastic zone contours in the slope when its upper layers are in a saturated state (Technogenic..., 2016). The primary soils actively involved in forming landslide deposits on the Dnipro slopes include loess-like loams, moraine loams, brown clays, and the upper layers of mottled clays. Under significant saturation from atmospheric precipitation, snowmelt, groundwater, or technogenic sources (leakage from water supply networks) water, high hydrostatic pressures (pore pressures) develop. These pressures act as a sharp trigger for the destabilization of the stress-strain state of the soil mass, specifically the destruction of structural bonds, leading to gradual movement of the soil mass along the slope.

In the study (Kril, Cherevko, 2023), mathematical modelling and observations of landslide hazard factors (surface deformations, crack openings in structural elements of buildings) on the slope of the Far-Caves Hill of the Kyiv-Pechersk Lavra identified potential locations. The study suggests that the identified boundaries of landslide and landslide-hazard zones should be extended deeper into the hill territory.

However, the determination of landslide-prone boundaries based on slip surfaces using risk analysis, which takes into account additional moisture through modern computational methods for calculating the stability factor, was not performed. This aspect was not addressed in the published works.

The main objective of this research was to identify the boundaries of landslide risk based on slip surfaces using risk analysis that considers additional moisture on the Dnipro slopes, employing mathematical modeling methods.

To achieve this, the following tasks were undertaken: collection and analysis of historical data and previous engineering-geological studies within the area; field investigations, including field observations of deformation signs on the slope and drilling of boreholes; analysis of natural deformation factors; modelling and stability calculations of the slope along three calculation profiles; and the development of recommendations for slope reinforcement in the zone of active interaction between soil and structures.

The study was conducted on a section of the Dnipro slopes near Mykilska Brama in the Pechersk district of Kyiv.

2. Research Methodology

The research utilized materials from engineering-geological surveys (Technical..., 2011, 2012, 2020), engineering-geological maps, and studies (Kolot et al., 1984; Demchyshyn, Kril, 2019). In 2020, with the participation of author A.O. Streltsov, drilling was conducted, and soil samples were taken for analysis. Based on the results, the geological and hydrogeological conditions of the studied area were analyzed (Technical..., 2020).

The physical and mechanical properties of the soils were determined based on laboratory test results and in accordance with state standards and building codes (Bases..., 1996a, b, 2001, 2009a; Soils..., 2016). Classification parameters (natural moisture content, plasticity index, moisture content at the liquid limit and plastic limit, plasticity number, liquidity index, granulometric composition) were obtained through laboratory tests on disturbed structure samples. Mechanical properties (internal friction angle, specific cohesion) and density were measured on undisturbed structure samples (monoliths). Deformation characteristics (compression index, compressive modulus) of the soils were obtained using oedometers that prevent lateral expansion of the soil sample during vertical pressure loading up to 0.3–0.6 MPa. Table 1 presents the values of the physical-mechanical properties of the soils in the studied area. To calculate the stability of the slope in the forecasted (saturated) state, the samples were saturated to full water saturation, followed by the determination of the corresponding characteristics. All data used in the calculations are up-to-date and comply with the requirements of DBN A.2.1-1-2008 regarding the validity period for engineering-geological surveys.

There are many methods for calculating slope stability, which depend on the number of assumptions made about the conditions of the limit equilibrium state at the points of the sliding prism, the shape and position of the potential slip surface, the distribution of normal forces along the slip surface, the relationship between the tangential and normal forces on the side faces of the blocks, as well as the degree of certainty regarding the slope parameters, etc. The methods for calculating slope stability are based on determining the relationship between the resisting and shearing forces acting on a portion of the soil (Duncan et al., 2014; Engineering..., 2017; Khan, Wang, 2020):

$$\mathrm{Kst} = \Sigma R / \Sigma T ,$$

where R is the resisting force to shearing; T is the shearing force.

It should be noted that the safety factor Kst obtained in this way is not a constant value. It varies seasonally and depends on the impact of external factors of both natural and anthropogenic origin.

The current building codes and regulations (DBN, DSTU) do not provide clear guidelines for the application of specific calculation methods. The choice of method depends on the engineering-geological conditions, the type of shear deformations, and the mechanism of potential soil displacement (Engineering..., 2017). Considering the engineering-geological conditions of the studied slope section and the analysis of calculation methods performed in works (Duncan, Wright, 2014; Khan, Wang, 2020), the Janbu method was selected among the limit equilibrium methods to determine the landslide-prone boundaries beyond the slip surface.

The analysis of changes in the slope stability factor was carried out by varying the moisture content factor and the corresponding changes in the physical and mechanical properties of the soils. The calculations were performed using the Janbu method for a circular cylindrical slip surface, implemented in the RocScience Slide 6 software (Analysis..., 2024).

The stability of slip surfaces was calculated using limit equilibrium methods for vertical slices. This method allows for the analysis of individual slip surfaces or the application of investigative methods to determine the critical slip surface for a given slope.

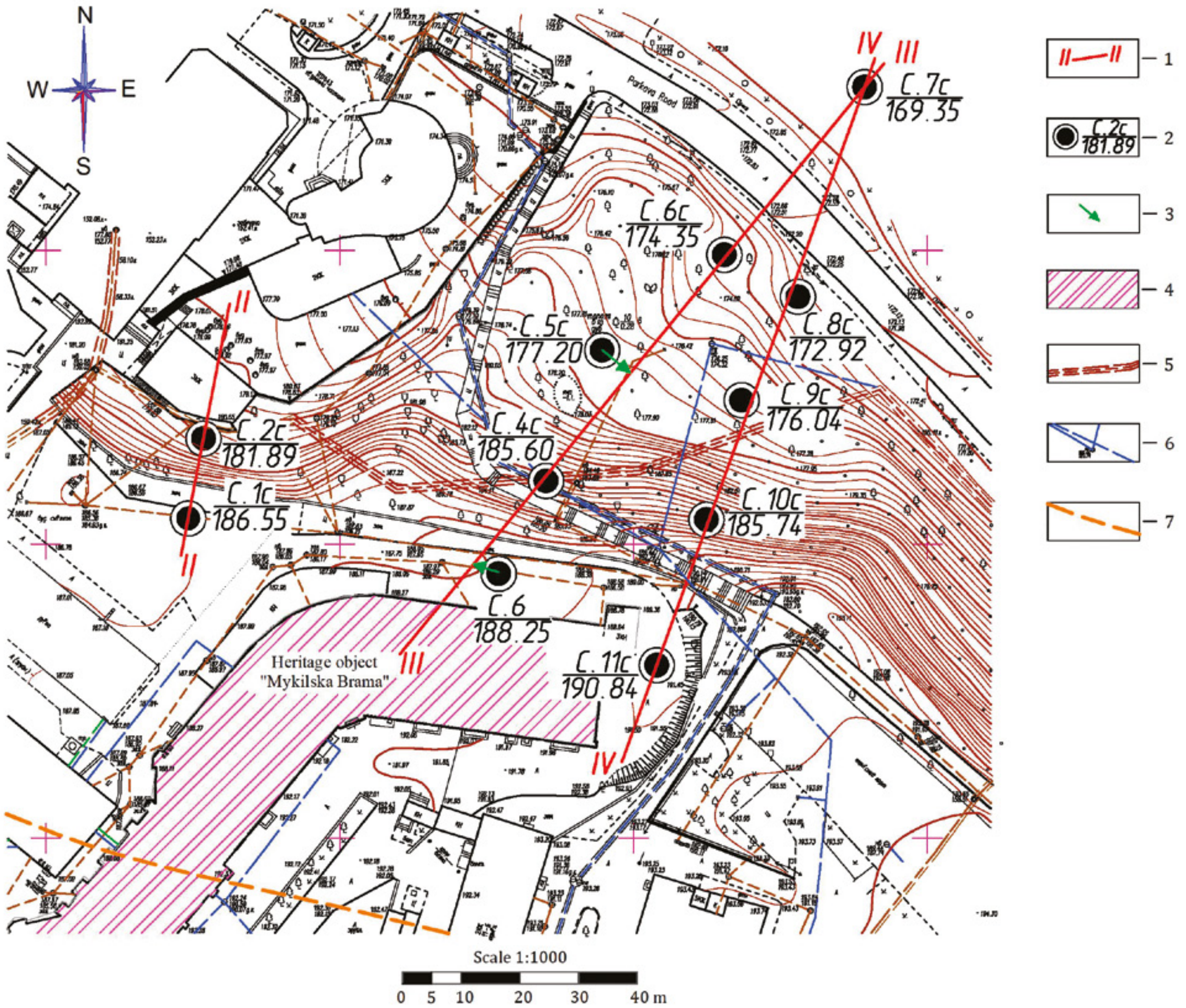

Fig. 1. The location of the stability assessment cross-sections within the study area: *1* – the cross-section line; *2* – observed wells (drilled boreholes); *3* – displacement of boreholes to the calculation profile line; *4* – the building of historical significance, Mykilska Brama; *5* – drainage-tunnel systems; *6* – water supply networks; *7* – the landslide hazard line according to the Scheme (Scheme..., 2020)

Table. Physical and mechanical characteristics of the soils of the slope near Mykilska Brama (Technical..., 2020)

No.	EGE	Description of the engineering-geological element (EGE)	Genesis, geological index	Liquidity index, IL, decimal quantity	Unit weight, γ, kN/m³	Void ratio, e, decimal quantity	Modulus of deformation, E, MPa	Calculated values (a = 0.95)		
								γ_I^*, kN/m³	φ_I^*, °	c_I^*, kPa
1	77	Bulk soils: sandy and silty loams	tH	0.17	17.0	0.890	7	16.7	19	8
		**Forecast saturation Sr = 0.8		–	18.4			18.1	17	7
2	16	Sandy loam, dusty, hard	dzH	-1.47	16.7	0.783	9	16.4	19	10
3	17	Sandy loam, dusty, plastic up to fluid		0.47	18.5	0.776	6	18.2	15	4
4	18	Sandy loam, plastic		0.53	18.4	0.695	12	18.1	17	7
5	19	Light silty loam, rigid, heavily peaty	bH	0.33	15.6	1.420	3.2	15.3	5	5
6	20	Light and heavy loam, dusty, soft plastic		0.52	17.5	0.906	8	17.2	10	9
7	1a	Sandy loam, dusty, hard, loess, subsidence	edv P_{III}-H	-1.18	16.6	0.814	13	16.3	22	16
		**Forecast saturation Sr = 0.8		0.73	18.3		6	18.0	16	6
8	2	Loam, rigid plastic		0.28	18.7	0.770	16	18.4	18	17
9	4	Dusty sand, low water saturation	f,l-g P_{II}dn	–	18.2	0.592	25	17.9	28	3
		**Forecast saturation Sr = 0.8			20.4		23	20.1	26	1
10	6	Heavy and light sandy loam, semi-hard	gP_{II}dn	0.16	19.7	0.598	27	19.4	14	41
11	7	Light and heavy loam, dusty, rigid plastic	lP_{I-II}	0.23	18.7	0.725	15	18.4	13	28
12	8	Clay is light and heavy, dusty, semi-hard		0.11	20.3	0.677	28	20.0	13	49
13	9	Light and heavy loam, dusty, rigid plastic		0.45	19.0	0.770	18	18.7	12	23
14	10	Clay is light and heavy, dusty, hard and semi-hard	N_2čb	0.02	20.2	0.672	32	19.9	9	137
15	11	Clay is light and heavy, dusty, hard and semi-hard	N_{1-2}sg	0.02	20.4	0.689	35	20.1	16	99
16	12	Sandy loam, hard	N_1np	-1.14	19.8	0.549	40	19.5	24	33

*γ_I – unit weight; e_I – void ratio; φ_I – soil friction angle.

** – values used in calculation for forecast state of slope.

The method for calculating the stability factor was chosen based on the results of test modeling of the IV–IV profile using the following methods: Simplified Bishop, Janbu, Spencer, GLE (general limit equilibrium)/Morgenstern-Price. The Janbu method yielded the lowest stability factor values. It is used for analyzing complex slopes (complex slope geometry, heterogeneous soils, complex loading conditions, changes in moisture conditions), where the assumption of circular sliding zones is not sufficiently accurate.

The behavior of the soils was characterized using the Mohr-Coulomb model. The calculated property characteristics of the identified engineering-geological elements were taken with a confidence probability of α = 0.95. The slope stability calculation in both the factual and forecasted states was performed along profiles II–II, III–III, and IV–IV, as shown in Fig. 1. The factual condition refers to the state of the slope that corresponds to the state of the soil massif in 2020, with existing buildings. The forecast state corresponds to the state when the soil layers IGE-77, IGE-1a, IGE-4 are subject to possible additional saturation, the values of physical and mechanical parameters corresponding to **Forecast saturation Sr = 0.8, see the Table. Data from individual actually drilled boreholes were used to construct the calculation profiles (indicated by an arrow in Fig. 1).

The identification of landslide-hazard boundaries for both the factual and forecasted states was performed on a topographic map based on the calculated slip surfaces at their extreme points along the slope edge. The spline method of the automated design system was used.

3. Results and Discussion

3.1. Engineering-geological features of the area

Administratively, the study area is located in the Pechersk district of Kyiv, at 1, I. Mazepa Street. The lower boundary of the studied area of the slope is Parkova Road, with the Dnipro River

Fig. 2. Markers of erosion-gravitational processes: erosion processes *(a)*, tilted trees, known as "drunken forest" *(b)*, photo by A.O. Streltsov, April 2020

located 350 m away. Almost at the edge of the slope lies the national architectural monument Mykilska Brama, part of the 19th-century Kyiv fortification system. At a depth of 1.5–2 m, water supply engineering networks are present. In the soil massif, at depths of 16–22 m, there are drainage-tunnel systems constructed with masonry that have been decommissioned. These systems were not considered in the calculations.

The engineering-geological conditions are complex (Technical..., 2011, 2012, 2020) due to the presence of soil layers prone to subsidence (more than 10 m thick). The slope angle varies between 20° and 43°, with an average value of 32–35°. The prevailing direction of the slope is northwest. The absolute elevation of the ground surface within the study area ranges from 168.0 to 192.2 m.

The relief of the studied area was formed as a result of active erosion processes, such as ravine and gully erosion, which occurred in the past, as well as subsequent land levelling during urban development activities.

The area borders the XV landslide circus according to the SMLPUW classification. The latest landslide displacement in this area occurred in 1953, with a volume of 800 m³ (General..., 1972).

Intense landslide activity occurred here between the mid-19th and early 20th centuries. Among other factors (vegetation, slope angle, lithological composition, etc.), the activation of movements on the Dnipro slopes was associated with the I and II aquifer horizons, which are widespread in the freshwater silty clay of the late-Quaternary-age and the sands of the Kharkiv series, respectively. This determined the block-type development of the landslide processes (Technogenic..., 2016; Bileush, 2009), as well as the flow of excessive moisture in the upper layers of the geological section, according to M.M. Maslov's classification (Maslov, Kotlov, 1972). In terms of plan form, they are classified as cirque-like according to E.P. Emelyanova's classification (Emelyanova, 1972).

At the same time, uncontrolled surface runoff created conditions for the development of erosion processes on the slopes, followed by the subsequent gravitational soil displacement along them. Considering the synergistic contribution of these processes in shaping the slope relief (landslide cirques), we find it important to further consider the development of erosion-gravitational processes, as they cannot be treated separately, for the central section of the Dnieper slopes in Kyiv. The impact of hydrogeological conditions on the formation of landslides is clearly expressed (Demchyshyn, 1992, 2001, 2019).

At present, no active landslide processes have been recorded in the study area. However, under excessive soil moisture, erosion-gravitational processes may become active. During field surveys of the site, signs and markers of erosion-gravitational processes were found: deep washouts, both planar and linear erosion, and a significant number of tilted trees, a phenomenon known as the "drunken forest", as shown in Fig. 2.

The groundwater levels in the boreholes at the time of the surveys in March 2020 were established at depths ranging from 5.0 to 14.5 m (179.59 to 162.35 m in the Baltic system) (Technical..., 2020). Within the upper plain area of the site, the absolute elevation of the groundwater table ranges from 179.59 m near Mazepa Street to 175.05 m at the edge of the slope. Along the slope, the levels vary between 175.00 and 162.35 m. Seasonal fluctuations in groundwater levels reach 1.5 m. The filtration direction is northeast, from the loess plateau towards the Dnipro. It should be noted that some boreholes exhibit abnormally high groundwater levels – 175.00 m. This is related to the formation of a perched water table due to losses from the water supply network running along the edge of the slope. The perched water table has a localized lens-shaped distribution.

The geological structure of the studied slope is generally typical of the central part of the Dnipro slopes. To a depth of 30 m, it is represented by the following deposits:

- tH – technogenic embankment soils, consisting of sandy loams and silty sands, which are dark gray, black, brown-gray, both firm and plastic, occasionally containing organic matter and inclusions of construction debris up to 25 % (broken bricks, rubble stone, wood, glass, scrap metal, etc.), with layers and lenses of stiff to soft plastic clay, 15 %, with a thickness of up to 10.4 m;
- d, dz, b H – Holocene complex of alluvial, alluvial-landslide, and marshy soils, consisting of silty sandy loams, ranging from hard to fluid consistency, and light, rigid, plastic loams, occasionally with organic matter and lenses of highly peat-accumulated soils. The thickness of the complex reaches up to 11.8 m in some areas;
- edv P_{III}-H – Eluvial-alluvial-eolian Late Neopleistocene-Holocene soils, represented by silty, loess-like, silty, hard and plastic sandy loams, light and heavy silty, tightly plastic loams. The thickness of the layer reaches up to 12.1 m;
- f,l-g P_{II}dn – Complex of Middle Neopleistocene deposits of fluvial, limnoglacial, and glacial genesis, represented by dusty, dense sands, sandy loams, and light and heavy loams of various consistencies. The thickness of the layer reaches up to 9.0 m;
- l P_{I-II} – Complex of Lower Neopleistocene limnic deposits, represented by firm and semi-firm clays, light and heavy silty clays, with a total thickness of up to 9.7 m;
- N_2čb – Deposits of the Neogene system, Pliocene (red-brown clays), represented by light and heavy silty clays, semi-firm and firm, with a thickness of up to 7.5 m;
- N_{1-2}sg – Deposits of the Neogene system, Lower Pliocene-Upper Miocene (mottled clays), composed of light and heavy clays, semi-firm and firm, with a thickness of up to 8.1 m;
- N_1np – Deposits of the Neogene system, Poltava series, represented by firm sandy loams with lenses of weakly cemented sandstone, with an exposed thickness of up to 6.3 m.

Within the studied area, 21 engineering-geological elements (EGE) were identified across three calculation profiles. The geological structure along profile IV–IV is shown in Fig. 3.

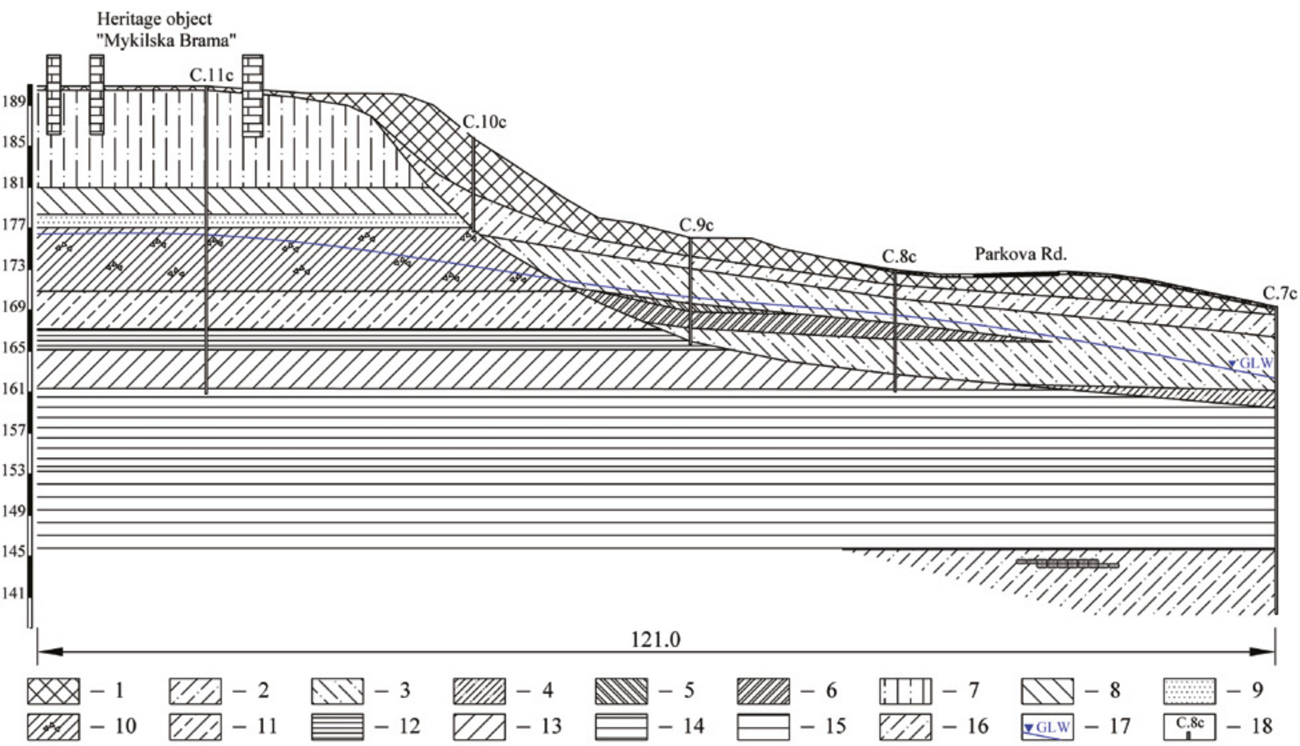

Fig. 3. Engineering-geological section along the profile IV–IV: *1* – EGE-77 – embankment soils: sandy and silty sandy soils (tH); *2* – EGE-16 – sandy loam with layers of fine sand and light clay (dzH); *3* – EGE-17 – sandy loam, dusty, plastic, occasionally fluid (dzH); *4* – EGE-18 – sandy loam, plastic, with layers and lenses of water-saturated sand (dzH); *5* – EGE-19 – light silty loam, rigid, heavily peaty (bH); *6* – EGE-20 – light and heavy loam, dusty, soft-plastic, with an admixture of organic matter (bH); *7* – EGE-1a – loess-like sandy loam, dusty, hard, subsidence (edv P_{III}-H); *8* – EGE-2 – light and heavy loam, dusty, rigid (edv P_{III}-H); *9* – EGE-4 – dense silty sand, ranging from low to fully saturated with water (f,l-g P_{II}dn); *10* – EGE-6 – loam heavy and light sandy, semi-hard, dense, with sand lenses (g P_{II}dn); *11* – EGE-7 – light and heavy loam, dusty, rigid (l P_{I-II}); *12* – EGE-8 – clay light and heavy dusty, semi-hard (l P_{I-II}); *13* – EGE-9 – light and heavy loam, dusty, rigid (l P_{I-II}); *14* – EGE-10 – clay light and heavy dusty, hard and semi-hard (N_2čb); *15* – EGE-11 – clay light and heavy dusty, hard and semi-hard (N_{1-2}sg); *16* – EGE-12 – sandy loam, hard, with thin lenses of sandstone (N_1np); *17* – boreholes; *18* – groundwater level as of March 2020 (Technical..., 2020)

3.2. Analysis of changes in the safety factor under excessive moisture condition

Slope stability calculations near Mykilska Brama were performed for both the factual state of the soils and the forecasted water-saturated condition. In the second case, the model incorporated the values of the physical-mechanical properties corresponding to the water-saturated state (forecasted state) for EGE-77, EGE-1a and EGE-4, see the Table. The results of the calculations provided the slip surfaces with the lowest safety factor – defined as the ratio of resisting to shearing forces on the slope – as well as the slip surfaces where the highest shear stresses would occur. The normative safety factor was taken as 1.25 in accordance with the regulations (Engineering..., 2017).

The slope along profile II-II is reinforced by several tiers of retaining walls, which were built during the construction of the residential complex at 9a, Hrushevskoho Street. These walls, along with the building structure, withstand the main shear pressure. In the factual state, the likely slip surface is located in the upper part of the slope, within the embankment soils. The safety factor Kst is 1.41, which exceeds the normative value and indicates a stable condition. In the forecasted state, Kst=1.19. This value is 4.8 % below the normative, but the slope remains stable, since Kst ≥ 1.

Along profile III-III, in the factual state, the slip surface begins behind the Mykilska Brama building and extends through the Lower Neopleistocene deposits

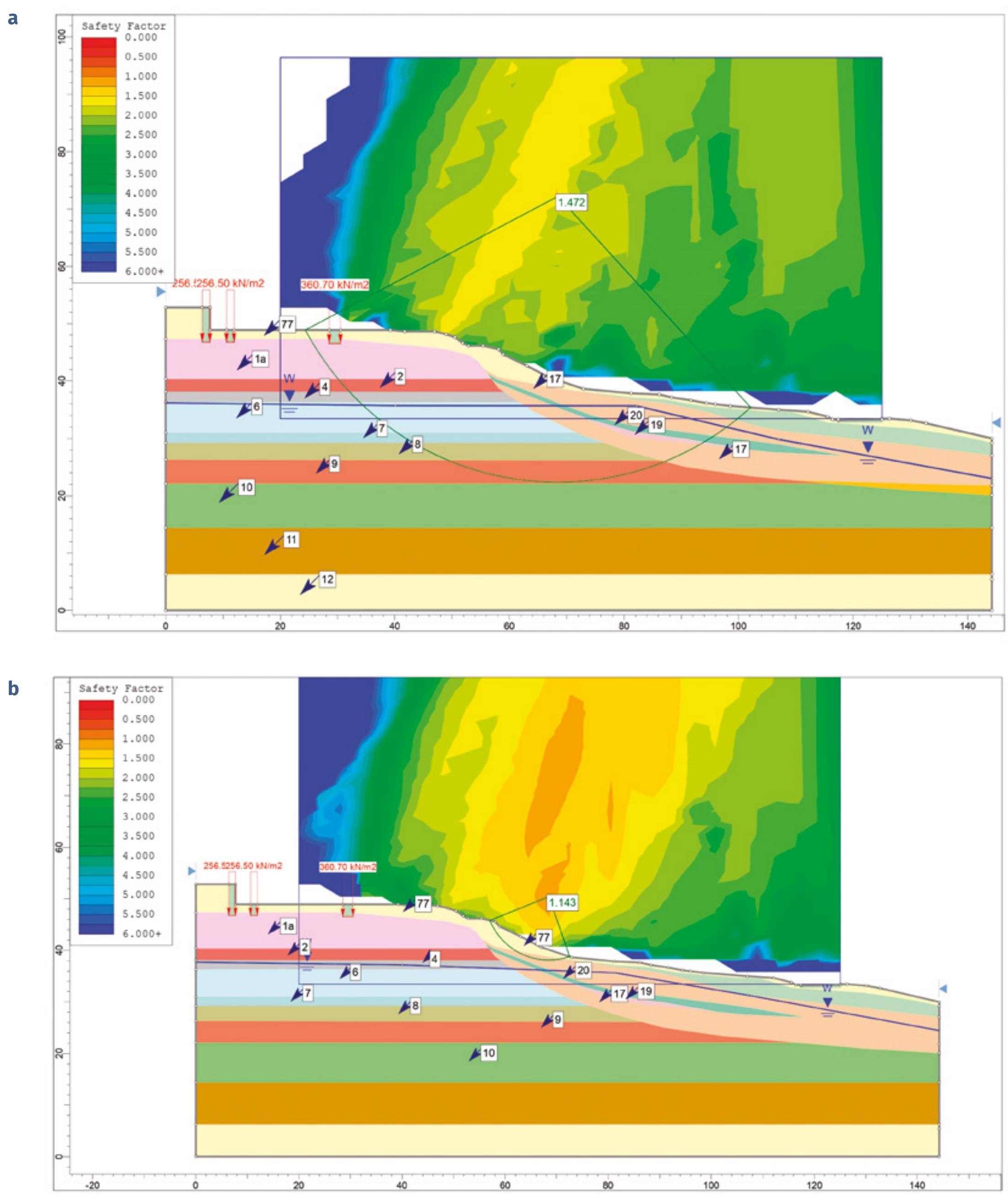

Fig. 4. The calculation models of the section along profile III–III in the factual *(a)* and forecast *(b)* states

of limnic genesis, which are lithologically represented by clays and silty clays. The safety factor Kst = 1.47. The slope is in a stable condition and fully meets the requirements of the normative safety factor.

In the forecasted state, the slip surface shifts to the steepest part of the slope and extends through weak, heterogeneous deluvial landsliding and embankment soils. The safety factor Kst = 1.14, which is 8.8 % below the normative value, indicating that the slope is approaching the state of limit equilibrium.

Along profile IV–IV, in the factual state, the slip surface passes through the embankment soils and has a safety factor Kst = 1.04. The obtained safety factor is significantly (16.8 %) below the normative value, indicating that this section of the slope is in a state of limit equilibrium. This is evidenced by the landslide markers recorded on-site: erosion, the "drunken forest" (see Fig. 2), and the formation of a crack in the slope. In the forecast state, the factor of safety reserve Kst = 0.932. Under such conditions, there is a loss of stability and activation of shear processes within the slope.

Fig. 4 presents the calculation models for profile III–III, where the changes in the position of the sliding surface were the largest.

The nature of the development of the most probable slip surfaces within the studied slope area indicates that under these conditions the development of landslide processes will occur on bulk, deluvial landsliding soils.

The specific relief of the area in the lower part of profile III-III suggests that, in the past, there was liquefaction of the soil mass of deluvial landsliding soils.

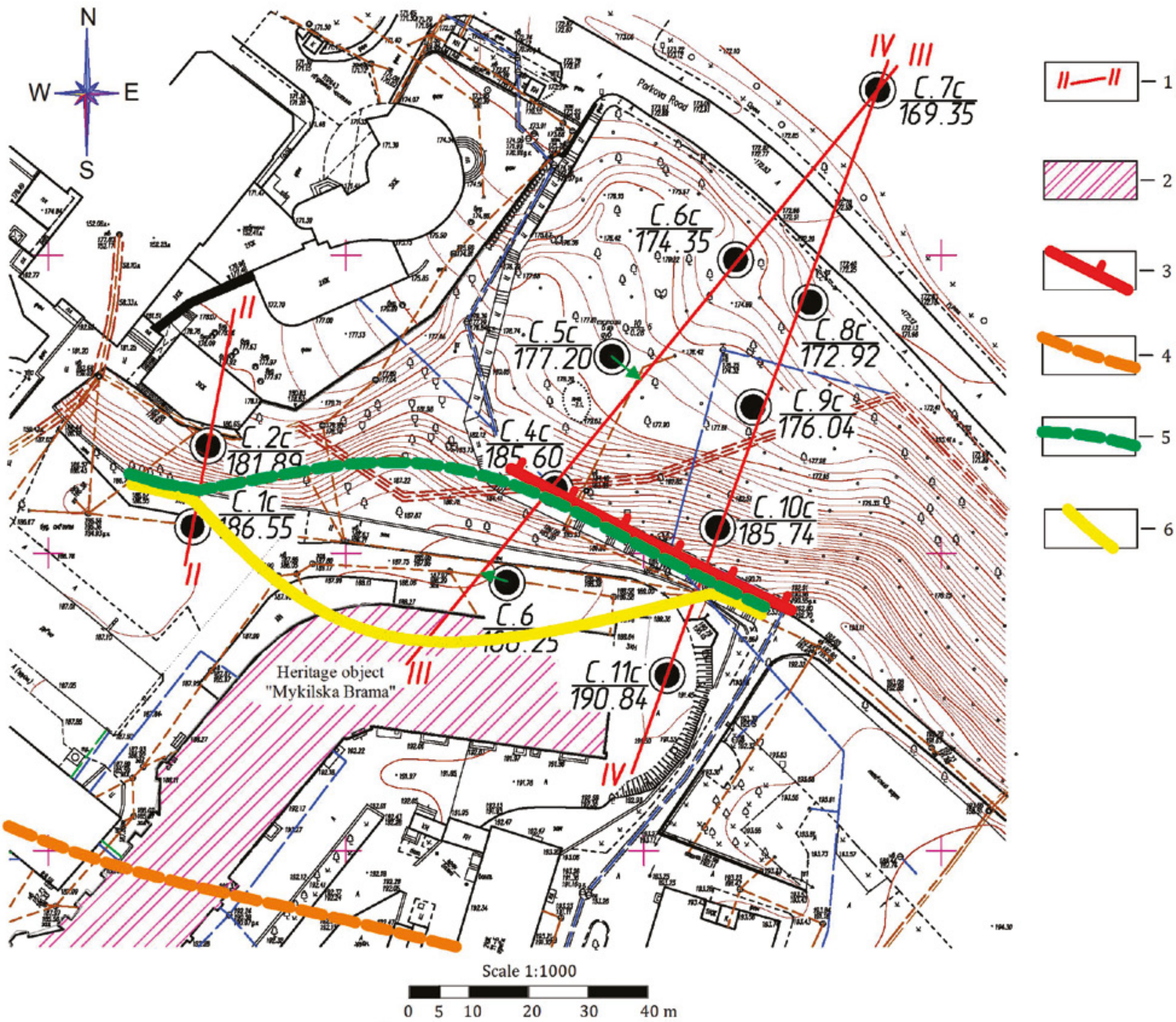

Fig. 5. Landslide-hazardous boundaries of the Dnipro slopes near Mykilska Brama: *1* – the cross-section line; *2* – historical structure, Mykilska Brama; *3* – crack-shear, determined by field observations; *4* – the landslide hazard line according to the Scheme (Scheme..., 2020); *5* – landslide-hazardous boundary of the forecast state; *6* – landslide-hazardous boundary of the factual state

To identify the factors affecting slope stability, calculations of the slope stability factor were carried out without the influence of preloading from existing structures. For calculation profiles III-III and IV–IV, it was determined that the decrease in Kst compared to the factual state is 14.5–22.5 %, and compared to the forecast state, it is 24.30–27.80 %.

It was noted that in the forecast state, the slip surface in the three calculation profiles is located above the groundwater table, so hydrodynamic pressures do not affect the stability factor. Pore pressure has a significant impact on the change in slope stability due to the reduction in effective stresses in the soil mass.

The combination of the upper boundaries of the sliding surfaces on the top plane allowed us to construct two types of landslide-hazardous boundaries for this slope, as shown in Fig. 5. The boundary drawn for the factual state of the slope extends deeper into the loess plateau compared to the forecast one. However, within these limits, the safety factor is higher and, accordingly, the safety margin of the soil massif is higher. Compared to the landslide hazard line according to the Scheme (Scheme..., 2020), the obtained boundaries are located 60 meters closer to the edge of the slope.

The calculations of the slope safety factor in the forecast state, in this case under conditions of soil moisture, show a decrease of 10.4 % for profile IV-IV, 15.1 % for profile II-II, and 22.4 % for profile III-III compared to the factual state. The greatest reduction in the safety factor (Kst) occurred in the middle profile III-III, which resulted in the displacement of the boundary of potential activation of erosion-gravitational processes by 30 meters toward the edge – the steepest areas of the slope.

The historical building of Mykilska Brama may be at risk of landslides and could experience deformation and damage, depending on the technical condition of its foundations and structures.

The landslide hazard boundary in the forecast state in the southeastern part of the site is located very close to the line of crack-shear recorded during field inspections. This indicates that the destabilization of the soil mass in this area is linked to the moistening of the upper soil layers, likely caused by leaks from the nearby water supply network.

According to the conducted modeling of the soil mass stability with additional soil moisture, the slope area requires the renovation of the water supply network, the regulation of surface and groundwater runoff, and the use of retaining engineering structures to ensure long-term safe use in accordance with DBN B.1.1-46:2017 (Engineering..., 2017). The landslide hazard boundary, considering the impact of additional soil moisture and the corresponding decrease in soil strength properties, has shifted by 30 m in the middle part toward the edge of the slope. In the case of displacement of a section of the slope along the embankment soils, the formation of new sliding surfaces may occur near the slope wall of the existing historical building.

The historical building of Mykilska Brama in the northeastern part requires the implementation of engineering protection measures. It has been recommended to reinforce the building's foundations using the jet-grouting method to prevent the effects of subsidence processes in loess-like sandy loams and to transfer the building's loads to well-consolidated glacial deposits.

To minimize and eliminate the impact of erosion-gravitational processes on safety and extend the operational lifespan of structures in the zone of active interaction, it is proposed to install a retaining wall made of bored piles below the most hazardous sliding plane, as identified in all profiles.

4. Conclusion

The slope area near Mykilska Brama has a complex geomorphological structure, with the presence of anthropogenic sources of soil water saturation, which lead to a differentiated soil moisture distribution and varying levels of surface erosion activity.

The main factors influencing slope stability in the studied area have been identified. These include the additional load on the slope from existing structures (resulting in a decrease in Kst of 14.5–22.5 %), the geometric parameters of the slope (such as the angles of inclination and height), the presence of anthropogenic soils and soils with low strength and deformation characteristics (for the study area EGE-17, EGE-19, EGE-20), as well as potential emergency leaks from the water supply network etc.

The scientific novelty lies in the fact that, for the first time, the landslide hazard boundaries for the Dnipro slopes near Mykilska Brama have been scientifically substantiated and established, both for current and forecast conditions, based on the position of the slip surface. The analysis was conducted using mathematical modeling, and the calculations were performed in the modern software application RocScience Slide 6. The determination of landslide hazard boundaries for two soil conditions (factual and saturated) allows for a clear differentiation of the risk levels of slope instability and material losses during landslide activation, which is crucial for urban planning.

The methodology for determining landslide hazard boundaries presented in the study serves as a practical tool for establishing such boundaries along the entire length of the Dnipro slope in Kyiv, as well as in other urbanized areas and for integrating them into Urban Design Master Plans at the regulatory level. At the same time, their construction should be based on properly substantiated geological and hydrogeological models of the slope, and the data on the physical and mechanical properties of the soils must be obtained in accordance with the requirements of DBN A.2.1-1-2008.

Identifying landslide hazards in slopes under two conditions (factual and forecast) allows for the differentiation of risk levels related to the loss of equilibrium in the soil mass of the slope and material losses in the event of landslide activation. The use of schemes developed based on this methodological approach in urban planning activities will contribute to minimizing risks in decision-making processes.

Вперше науково обґрунтовано та встановлено межі зсувної небезпеки для ділянки схилів Дніпра в районі Микільської брами як у фактичних, так і прогнозованих умовах за положенням площини ковзання. Дослідження виконано на основі ризик-аналізу активізації зсувів, що враховує додаткове зволоження як наслідок впливу аномальних метеорологічних та техногенних факторів. Положення поверхонь ковзання обґрунтовано значенням нормативного коефіцієнта стійкості. Їх виділення виконано на основі математичного моделювання для трьох профілів на схилі при природних показниках фізико-механічних властивостей та у прогнозованому (замоченому) стані. Розрахунки проведено у програмному комплексі RocScience Slides 6, застосовано метод Янбу круглоциліндричної поверхні ковзання. Інженерно-геологічні умови даного схилу охарактеризовано як складні через наявність товщі просідних лесових ґрунтів, кутів нахилу 20–43°. При натурних спостереженнях зафіксовані ознаки ерозійно-гравітаційних процесів, зокрема «п'яний ліс» та тріщини заколу. Основним фактором втрати рівноважного стану ґрунтів на схилі є перезволоження, що може бути як наслідком аномальних атмосферних опадів, так і надходження в ґрунти техногенних вод через витоки з мереж водогону. За розрахунками коефіцієнта стійкості схилу у прогнозованому стані, у даному випадку при перезволоженні ґрунтів встановлено його зниження на 10,4–22,4 % у порівнянні з фактичним станом. Зсувонебезпечна межа при врахуванні впливу додаткового перезволоження ґрунтів та відповідно зниження міцнісних властивостей ґрунтів змістилась на 30 м у середній частині у бік брівки схилу. Наведена у дослідженнях методика проведення зсувонебезпечних меж є практичним інструментом для побудови таких меж на всій протяжності дніпровського схилу в м. Київ. Виділення зсувної небезпеки схилів за двома станами дозволяє диференціювати рівні ризиків втрати рівноважного стану ґрунтового масиву схилу, матеріальних втрат при активізації зрушень.

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