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Assessing stability and landslide hazard risks on kyiv's dneiper slopes: a zoning methodology

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SUMMARY

The Dnipro slopes in Kyiv represent an area of elevated landslide risk due to complex engineering-geological conditions, particularly the widespread presence of loess soils, steep terrain gradients, and the combined impact of meteorological and technogenic factors. The aim of this study was to zone the slopes based on their stability and relative landslide risk using geoinformation technologies. The methodological approach integrated a scoring system for slope stability factors (slope angle, soil type, moisture content via NDMI) with the classical risk assessment formula: Risk = Hazard × Vulnerability × Exposure.

The study combined geological data, remote sensing results (NDMI index from Sentinel-2), topographic plans, and information on buildings and engineering infrastructure into a unified GIS-based project. The Landslide Hazard component was evaluated using a weighted scoring system based on slope angle, soil classification, and moisture conditions. Risk values were normalized, and vulnerability and exposure were assessed for typical urban elements (buildings, roads, underground structures, green areas, etc.).

The results showed that 27.2% of the study area has a landslide probability exceeding 0.5, with 9% classified as high-risk zones. The resulting risk maps enable the localization of hazardous areas, support the optimization of monitoring systems, and assist in prioritizing engineering protection measures. The findings have practical value for urban planning, heritage preservation, and enhancing safety on the urbanized slopes of Kyiv.

Introduction

The Dnipro slopes in Kyiv represent a high-risk zone due to steep terrain inclinations, heterogeneity of soil composition, seasonal fluctuations in moisture regimes within the soil mass under meteorological influences, and emergency leakages from technogenic sources. These risks are further exacerbated by increasing urban pressure resulting from intensive urban development activities (Kril, Streltsov, 2025). Climate change – including increased precipitation intensity and snowmelt – intensifies the potential for erosion and landslide development on these slopes. Urbanization processes in the city, particularly construction on slopes, necessitate a precise and integrated assessment to support effective planning and disaster prevention.

Multiple approaches exist for risk assessment. In general terms, risk is interpreted as the potential for future damage or adverse outcomes resulting from hazardous events, often equated with danger itself or the presence of a hazardous process. Other definitions emphasize risk as the likelihood or probability of a harmful event or process. The most commonly used understanding defines risk as a probabilistic measure of danger for a specific object, expressed in potential material or human losses over a defined period (European..., 2015; Rudko et al., 2017; Shekhunova, Kril, 2022; Streltsov, Kril, 2025). Risk analysis is not only a tool for disaster mitigation and prevention but also a crucial step towards achieving coordinated development of the environment, economy, and society. It also supports the implementation of global sustainable development goals within climate adaptation strategies (Kasiyanchuk et al., 2016; Shu et al., 2025; Capobianco et al., 2025).

The aim of this study is to develop a methodology for zoning the Dnipro slopes within the Kyiv area based on slope stability and the relative landslide risk for structures located within the study zone. To achieve this objective, geological data, remote sensing outputs, topographic maps, and structural characteristics were compiled and integrated into a unified GIS-based project. The probability of landslide occurrence was calculated, and available information on structures and engineering facilities within the delineated area was analyzed. Classification scales were developed to categorize objects according to their vulnerability and exposure.

The study was conducted on a section of the Dnipro slopes between Navodnytska and Hlybochytska gullies. The relative landslide risk was assessed for the following categories of objects: buildings and structures, roads (including highways and pedestrian paths), underground drainage facilities, retaining walls, parks, and green zones. The risk was quantified in relative units, without assigning monetary values to the assessed objects.

Materials and Method

The methodological framework for slope zoning and risk analysis of erosion-gravitational hazards on the Dnipro slopes integrates two complementary approaches: a scoring system based on slope stability factors and a classical risk evaluation using the formula ($\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Exposure}$).

The scoring method for slope stability assessment involves evaluating each unit area (grid cell) based on a set of key factors influencing slope stability. Each factor is assigned a specific number of points according to its degree of impact, and the resulting scores are summed to generate a hazard map. To determine the relative value of Hazard, three factors were considered: slope angle, the type of Quaternary deposits (referred to as First Soil Type), and the degree of surface moisture. The classification criteria are provided in Table 1. The total score for each cell was normalized on a scale from 0 to 1, where 0 represents min landslide probability and 1 indicates max probability.

The classification of soil types was developed with regard to the geological features of the Dnipro slopes, with displaced (remolded) soils allocated into a separate category. Sandy soils (containing more than 50% sand) are highly resistant to landsliding under natural conditions due to their medium to high structural density and a high angle of internal friction (30–34°), which provides good mass stability under loading. Sandy loam soils are composed of a mixture of sand (30–50%) and silt particles (20–50%). They exhibit moderate permeability and tend to become unstable when saturated, increasing the risk of erosion and localized landslides.

Table 1. Gradation of factors for the relative Landslide Hazard Analysis

Factor	Gradation	Index	Cell area within the study area, %
Slope, α	$\alpha \leq 5^\circ$	1	33,75
	$5^\circ < \alpha \leq 15^\circ$	2	13,86
	$15^\circ < \alpha \leq 25^\circ$	3	15,00
	$25^\circ < \alpha \leq 35^\circ$	4	25,98
	$\alpha > 45^\circ$	5	11,42
First Soil Type	Sandy soils	1	8,75
	Sandy loam soils	2	20,20
	Clay soils	3	6,15
	Displaced soils	4	25,51
	Loess soil	5	39,40
NDMI	< 0.1	1	49,07
	0.1-0.2	2	32,86
	0.2-0.3	3	12,07
	0.3-0.5	4	5,50
	≥ 0.5	5	0,51

The presence of silt reduces shear strength under wet conditions, resulting in a medium hazard rating. Clay soils (clays and heavy loams) demonstrate a high susceptibility to landslide formation. Landslide slip surfaces most frequently develop within these soils. A notable example is the landslide terrace within the study area along Parkova Road, which is associated with Neogene red-brown and variegated clays. In these formations, slip planes typically evolve in subhorizontal orientations, with dip angles ranging from 7° to 12° . This behavior is attributed to the low internal friction angle of clayey soils ($10\text{--}16^\circ$) and the presence of weakened zones – so-called consolidation fissuring.

Displaced soils, formed as a result of previous landslides, have a disrupted structure and heterogeneous composition (loess, clayey, or loamy components). These soils possess reduced strength and heightened sensitivity to reactivation. They are also highly favorable for the formation of perched water and localized saturated zones, thus presenting a high risk of renewed gravitational processes. Loess soils are macroporous and rich in silt-sized particles ($>50\%$), cemented by easily soluble carbonate-clay binders. While stable and strong in a dry state – capable of maintaining vertical slopes up to $15\text{--}25$ m – they are prone to collapse upon wetting. This property poses a significant hazard in urbanized, technogenically loaded slope environments. Water dissolves the carbonate-clay cement, causing a sharp reduction in soil strength and triggering subsidence.

The degree of soil moisture was indirectly assessed using remote sensing data by calculating the Normalized Difference Moisture Index (NDMI) based on Sentinel-2 imagery. NDMI was computed as the ratio between near-infrared radiation (NIR – Band 08) and shortwave infrared reflection (SWIR – Band 11) values (Index..., 2025).

Slope gradients were derived using the “Slope” tool in ArcGIS (ArcGIS..., 2025), based on vectorized contour and elevation data extracted from topographic maps. The classification of slope angles follows the criteria set out in Demchyshyn (1992).

In the risk formula, Vulnerability reflects the extent to which objects or systems (e.g., people, buildings, infrastructure, parks, forests) can be damaged due to landslides or erosion. In the GIS environment, vulnerability values were assigned to each object based on location: buildings and structures (depending on whether located on slope, edge, or plateau): $0.2\text{--}1.0$; roads: $0.6\text{--}0.8$; retaining walls: $0.1\text{--}0.3$; underground structures: $0.2\text{--}0.8$; parks and green zones: $0.1\text{--}0.2$.

These values were normalized on a $0\text{--}1$ scale (0 – no damage, 1 – maximum vulnerability), taking into account the surface area of each object within a unit grid cell.

Exposure indicates the presence and value of objects that may be affected by a landslide. It considers population density, the economic worth of assets, and their societal importance. The following

relative exposure values were assigned: buildings and structures (residential, administrative, cultural heritage): 0.5–1.0; roads: 0.6–0.8; retaining walls: 0.4–0.7; underground structures: 0.5–0.7; parks and green zones: 0.1–0.4. Exposure was also normalized to a 0–1 scale, proportionally to the area of the object within each unit cell.

Geological conditions of the study area were analyzed using the geological map (Kolot et al., 1984), geodetic plans (scale 1:2000), and engineering protection schemes (scale 1:1000). Sentinel-2 multispectral satellite imagery was used to generate a composite NDMI mosaic.

All input data were converted to the Universal Transverse Mercator (UTM) coordinate system (WGS84 datum, zone 36 N) and processed in ArcGIS version 9.3. A grid-based assessment method was applied, with the study area divided into unit cells of 25×25 m. The layers of buildings and infrastructure were vectorized from topographic maps and engineering protection schemes.

Results

Within the study area, the following deposits were identified within the depth range potentially involved in landslide processes: alluvial sediments of the floodplain (aH) and the first above-floodplain terrace (a¹P_{III}df-pc), loess-like deposits (e, vd P_{I-II}, e, vd P_{III}), Neogene clays (N₁₋₂), proluvial formations (pH), and displaced (remolded) deposits (grH, d P_{III-H}), among others.

In addition to geological parameters (soil type, lithology, and layer thickness) and the moisture regime, relief and slope steepness play a critical role in the development of hazardous geological processes. According to work (Demchyshyn, 1992), loose sandy-clay soils in areas with slope angles up to 5°40' typically do not exhibit significant movement or deformation that would pose a threat to structures or human safety. However, in areas with inclinations between 5°40' and 11°20', clay soils may undergo deformation and displacement as a result of moisture-induced changes in consistency – transitioning from firm to plastic or fluid-plastic states. These changes may occur due to atmospheric precipitation, technogenic water infiltration, or the rise of groundwater levels.

Figure 1a presents the spatial distribution of landslide hazard, calculated based on three primary factors: slope angle, First Soil Type (Quaternary deposits), and NDMI (Normalized Difference Moisture Index). The analysis shows that 27.2% of the study area exhibits a probability of landslide occurrence exceeding 0.5, indicating elevated levels of hazard.

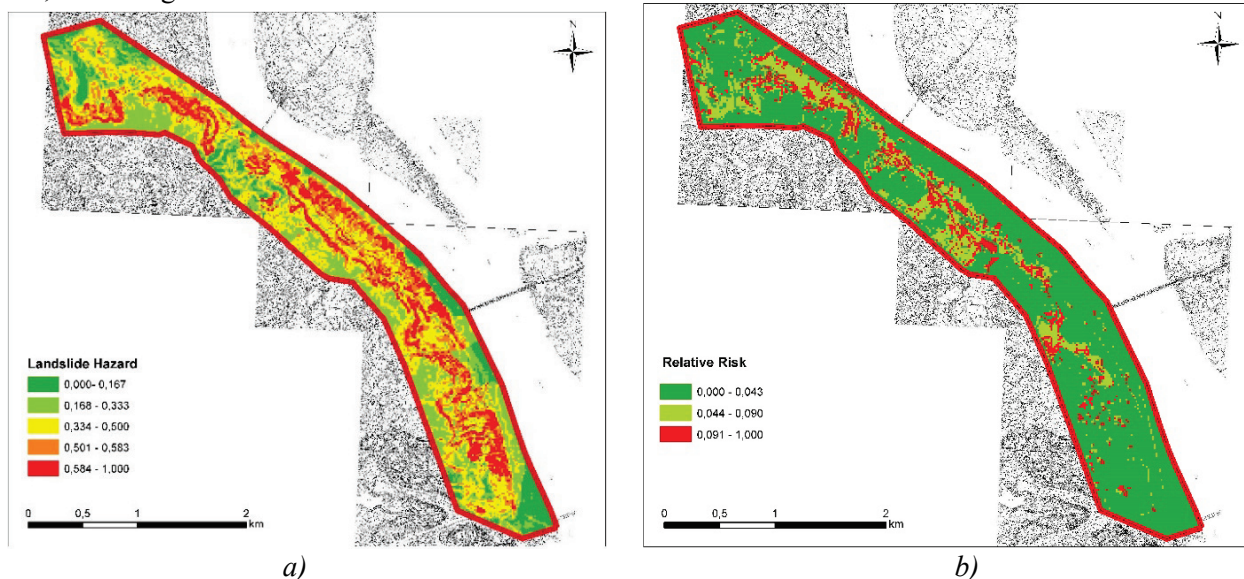


Figure 1 Figure showing the distribution of Landslide Hazard (a) and the relative risk level for infrastructure and facilities on the Dnipro slope exposed to landslide hazard (b).

The obtained relative risk values were classified into categories (see Figure 1b) as follows: 0.00–0.043: Low risk – landslides are unlikely, and objects are either absent or not vulnerable; 0.044–0.090: Medium

risk – potential hazard is present; monitoring or preventive measures are recommended; 0.091–1.00: High risk – high probability of landslide occurrence affecting vulnerable and valuable assets; immediate mitigation measures are required.

In terms of area coverage, high relative risk zones account for 9% of the study area, medium-risk zones for 15%, and low-risk zones for 76%. The majority of engineering structures and infrastructure are located within the plateau zone.

Conclusions

The distribution of landslide hazard, based on the selected assessment criteria, indicates its spatial association with the edge zone of the loess plateau and the landslide terrace. The relative risk map for objects on the Dnipro slope reveals localized, point-specific concentrations of elevated landslide risk. This spatial pattern allows for the design of optimized geotechnical and environmental monitoring, enabling the selection of appropriate instruments at the object-specific level. These may include piezometers, inclinometers, extensometers, velocimeters, accelerometers, and other devices to ensure slope stability and protect the historical, cultural, natural, and architectural heritage of the city.

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