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The 'Umka' landslide

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ABSTRACT
We present an in-depth landslide map of the 'Umka' landslide near Belgrade, Serbia, at a scale of 1:5000. The map delineates elements at risk, primarily buildings and road infrastructure impacted by the landslide displacements of several cm per year, introduced during frequent reactivation stages. The Main map results from a survey of over 350 buildings and more than 7 km of state and local roads. The acquisition techniques included engineering geological field mapping, building survey, and visual interpretation of high-resolution UAV images. This is the first case of an integrated approach to mapping elements at risk within an urbanized active landslide in Serbia. Presently, over 490 people continue to reside at the site, facing daily landslide risks. This research and map hold substantial value for local authorities and decision-makers, providing a basis for conducting landslide risk analyses and implementing effective risk mitigation strategies or remedial measures.

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KEYWORDS
Landslide risk; elements at risk; drone mapping; building survey; geotechnical monitoring

Key Science Highlights

- This study provides the most detailed, thorough, and accurate map of the 'Umka' landslide damage distribution that affects terrain surface, numerous buildings, and road infrastructure.
- We demonstrated an integrated approach applied to mapping elements at risk from landslide, which included detailed engineering geological mapping and detailed geotechnical investigations along with building surveys, and visual inspection and interpretation of high-resolution UAV images.
- Damage classifications with detailed descriptions enable better implementation of the map as an official document by local authorities and more efficient decision-making.

1. Introduction

The state-of-the-art in engineering geological and geotechnical aspects of landslide research and management rarely consider analysis of landslide impact on elements at risk, such as urban fabric, traffic, etc. Consequently, the corresponding mapping outputs, such as thematic landslide maps on site-specific scale are also rare. Regional landslide inventorying (Bernat Gazibara et al., 2019; Borrelli & Muto, 2017) and landslide susceptibility mapping, especially in regional or national scales (Segoni et al., 2016), is by far more common in research, while landslide hazard is somewhat more common in planning and design practice at regional to local scales (Martinello et al., 2023), but maps at site-specific scales are rarely addressed, primarily due to a lack of data on individual landslide impact. Only with impact determined, the final risk can be estimated, and the landslide workflow can be completed. Susceptibility or hazard assessment, although they go hand-in-hand with risk assessment, can serve only as partial solutions.

Site-specific scale landslide maps are essential for detailed risk assessment and targeted mitigation efforts in areas particularly susceptible to slope instability. Unlike regional maps, which provide a broad overview, these detailed maps offer precise information on the specific characteristics of a site, including slope angle, soil composition, cross-sections and existing land use. This level of detail is crucial for engineers, planners, and emergency responders in designing effective countermeasures for safeguarding communities and infrastructure.

Studies of this nature are imperative for consolidating landslide databases, particularly given the often-non-systematic landslide data (Corominas et al., 2013). Comprehensive maps and databases play a crucial role in understanding past landslide events, directing limited resources toward optimal risk assessment techniques (Sultana, 2020). The efficiency of predictions and mitigation measures hinges significantly upon the completeness and precision of landslide databases (Guerrero et al., 2012). The identification and assessment of hazards, but also the effect and

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damage inflicted, constitute essential strides in reducing landslide risks through disaster mitigation planning (Bera et al., 2019).

A primary objective of the hazard map and subsequent risk map is user-centricity (Shen et al., 2023), designed to facilitate their use by professionals, regulators, educators, and other stakeholders in civil engineering, environmental consultancy, planning, hazard management, or education. Following such agenda, a map of the landslide 'Umka', near Belgrade (Serbia) is presented in this paper. Acknowledging the challenges reported in communicating landslide maps to non-experts, the detailed, site-specific, map of the Umka landslide offers easily interpretable information, from landslide setting, investigations conducted, and damage to buildings and infrastructure (as key elements in risk determination), to raise awareness and enhance public preparedness. The terminology employed aligns with landslide risk and hazard definitions proposed by Fell et al. (2008) and Corominas et al. (2013).

2. Study area

The Umka settlement is located in the southwestern part of the Čukarica municipality, a part of the City of Belgrade, bordering the Obrenovac city to the west. Strategically positioned along the right bank of the navigable Sava River, it intersects State Road N°26, connecting Belgrade with surrounding areas, with over 13,500 vehicles on average daily passing over the landslide body.[1] The settlement lies mostly between the Sava River and the state road, with some areas extending toward the nearby Sibovik and Stepašnica hills. As of the 2021 census, the population of Umka decreased to 4,985, down from over 5,200 in 2011 (0.4%/year).

2.1. Geological setting

The area around Umka exhibits a complex stratigraphy characterized by a sequence of Miocene sediments and their weathered and remoulded counterparts. The landslide named 'Umka' after the settlement itself, was primarily formed through the gravitational movement of certain portions of these sediments towards the Sava River, with a dominant WNW direction. The sliding process primarily affected decomposed, oxidized yellow Miocene marly clays (M_3^2) and dark-brown, silty-sandy clays (d_{pr}) of deluvial origin (Jelisavac et al., 2006). These marls are typically soft to firm and form the uppermost layers of the stratigraphic column, making them highly susceptible to sliding and deformation when disturbed by natural processes or human activities (Jelisavac et al., 2006). Beneath, the fresh grey marls (M_3^2L) of unknown depth are forming the base, and typically are not involved in the sliding. In fact, it predominantly occurs in the interface of marly clays and marls (Figure 1).

In the landslide body itself (ko_a^{gl}) is composed of loose and unconsolidated mixture of clays, silts, and sands derived from the weathering of the underlying rocks. This material is highly prone to sliding reactivation (seasonally and annually), characterized by numerous cracks and voids that vary in size and shape depending on movement and saturation levels (Abolmasov et al., 2015). These cracks, which can range from cm to dm in aperture and reach depths of up to 5 m from the ground surface, can partially or completely close after the soil regains moisture during rainy periods (Abolmasov et al., 2015; Đurić, 2020). As a result, there is a significant spatiotemporal anisotropy (both horizontal and vertical) in the geotechnical characteristics of the soil, which also complicates the fluctuation of the groundwater table. Within these colluvial deposits, sandstone lenses are occasionally present. These fine-grained sandstone layers are more resistant to erosion compared to the surrounding clays and may act as localized zones of stability or as slip surfaces depending on their orientation within the landslide body (Jelisavac et al., 2006). Due to all the conditions described above, and as

Figure 1. Field images of outcrops on the face of a secondary landslide scar, with typical remolded material with heterogeneous lenses and undulating interfaces (left); and the core box of borehole Bi 14, where interface of fresh marl and remolded clay marl, representing the slip surface, is visible (right); Photo by Svetozar Milenković.

confirmed through a long-term geotechnical monitoring of the site, the landslide body can be split into three independent blocks which have different level of activity, as well as displacement rate and associated damage.

The geological structure of the Umka area is further influenced by several faults that have shaped the landscape. These faults, typically normal or strike-slip, contribute to the deformation of the Miocene deposits and impact the drainage patterns and groundwater flow in the region (Đurić, 2020). The marly clays and associated lithologies are often heavily fractured, with numerous joints and minor faults intersecting the stratigraphy. These fractures facilitate groundwater movement, and by increasing pore water pressures within the sliding mass, cause the landslide reactivation (Abolmasov et al., 2015). The broader tectonic setting of the region, as part of the Pannonian Basin, features complex subsurface structures with folded and faulted strata, contributing to slope instability in the Umka area (Vujanić et al., 1984). However, surface water dynamics, the Sava River in particular, are predominantly controlling the landslide displacement patterns. The draw-down effect noticed seasonally (Abolmasov et al., 2015) directly corresponds to landslide reactivation and acceleration.

Surface features reveal the stratigraphic complexity and active processes in the region. Outcrops of marly clays and silty sands are visible along the riverbanks and slopes leading to the Sava River, showcasing signs of weathering and deformation such as tension cracks and shear zones (Jelisavac et al., 2006). The main scarp of the Umka landslide, along with secondary scars, marks the areas of significant ground displacement and exposure of underlying lithologies (Abolmasov et al., 2015; Đurić, 2020).

The body of the landslide is predominantly plastic to brittle-plastic, with a very soft zone in the sliding surface and shear zone within the blocks. The water permeability and draining ability of the colluvium is weak, with underground water primarily flowing through the cracks. The infiltration of surface water and wastewater, in conjunction with the existing groundwater, further degrades the rock mass and reduces its geotechnical properties and parameters. Water saturation is more pronounced in the near-surface parts of the terrain at depths of 5–8 m, corresponding to the zone where the most of existing and abandoned wells for supplying households with technical water were constructed (Đurić, 2020; Jelisavac et al., 2006; Vujanić et al., 1984).

The landslide is classified as an active earth slide with a variable sliding surface depth – 3 to 10 meters uphill and over 20 meters between the state road and the Sava River – forming a convex sliding plane (Hungr et al., 2014). Surface deformations include secondary scars, tension cracks, bulging, ridging, gullying, and 'drunk' trees, with significant infrastructure damage observed throughout the affected area (Abolmasov et al., 2015; Đurić, 2020).

2.2. Earlier engineering geological investigations

Engineering geological investigations within the area of the landslide have been conducted multiple times from 1978 to 2010. The most extensive and detailed investigations were carried out by the Highway Institute – Belgrade for the Conceptual Design of Highway E-763, specifically Section 2: Umka-Obrenovac, and were conducted in three distinct periods: 1980, 1990–1991, (Vujanić et al., 1995). and for the Main Design phase in 2005.

The results of the extensive engineering geological investigation, geotechnical monitoring, and laboratory testing carried out in the 'Umka' and 'Duboko' landslides from 1990 to 1991 greatly expanded previous understanding of landslides formed in the Neogene in Serbia (Abolmasov et al., 2014). These investigations also enabled the interpretation of the structure of the sliding body, monitoring of changes in porosity, humidity, water permeability, and the genesis, position, and significance of discontinuities. The precise determination of the shape, dimensions, and depth of all active and potential sliding surfaces as well as the characterization of the bedrock itself was also made possible.

The 2005 engineering geological investigation supplemented and reinterpreted the 1990–1991 research, with a focus on previously unexplored areas of the 'Umka' landslide. The study, a continuation of earlier work, showed a strong correlation with sliding surface depths established in 1990–1991. Significant changes were noted in groundwater levels and surface geomorphological features. Additionally, new knowledge on the dynamics of the landslide was gained through the observation of many inclinometers (Jelisavac et al., 2006), surface deformation monitoring using the permanent GNSS of a fixed point (Abolmasov et al., 2021), and surface deformation monitoring using remote sensing techniques (Abolmasov et al., 2012; Đurić, 2020). The position of all previous geotechnical investigations is shown on the Main map.

3. Methods

The map represents a holistic overview of the Umka landslide at a site-specific scale, containing its geometrical representation, displaying relevant historical investigations (conducted in past couple of decades) and its effects on the urban fabric. The latter is, however, of the most relevance and entails a specific methodological approach. It was necessary to conduct an in-depth overview of available historical data, map the current surface conditions and qualify and quantify the landslide damage to affected infrastructure and objects. The methodology of earlier investigations that were used in this work will not be described in detail, as they can be found in the original publications as follows:

- Engineering geological properties and map (Jelisavac et al., 2006)
- Engineering geological properties and landsliding mechanism (Abolmasov et al., 2015)
- Landslide dynamics (Abolmasov et al., 2021; Đorđević et al., 2022)
- Landslide topography (DTM), census data, traffic data and elements at risk map (Đurić, 2020).

3.1. Supplementary engineering geological mapping

All engineering geological findings, including maps, borehole logs, soil samples, and geomechanical laboratory results were adopted from earlier works (Abolmasov et al., 2015; Đurić, 2020; Jelisavac et al., 2006) to gather information on the soil and rock types present in the area as well as their geotechnical characteristics, such as strength, stiffness, and permeability.

Additional engineering geological mapping was conducted for this work, to provide an update that can be used to evaluate the current engineering geological conditions of a site and determine its suitability for various uses. The information collected during these surveys in combination with data available from earlier investigations was used for compile a detailed map of the engineering geological properties of the area.

During the mapping, the presence and position of new scars, the occurrence of ponds and diffuse seepage of water on the terrain surface, the water levels in active wells, and a list of damaged buildings were determined. Mapping of neighboring watersheds was also carried out to survey the wider area of the landslide. The mapping data was further supplemented with data collected through remote sensing, existing technical documentation, and data obtained through one control exploratory well. The presence of functional wells for water supply and their water levels were also recorded to determine the estimated level of groundwater during the mapping period.

The results of the mapping represented a supplement to the existing research, as the scope of the previous research was deemed satisfactory. However, the need for remapping arose due to the lengthy period of 12 years since the previous research.

3.2. Building surveying

A building survey is herein regarded as a detailed examination of a property, typically a residential building (house or facility), to evaluate its condition and identify any potential issues or defects. It is typically conducted by professional surveyors using specialized equipment and techniques to inspect the property and produce a report of their findings. It is conducted by using a unified questionary, which is based on internationally approved works (Alexander, 1986; Chiocchio et al., 1997) as well as some new insights (Del Soldato et al., 2017), but also domestic experiences (Đurić et al., 2022), as every landslide region is somewhat specific.

Such a survey entails an in-depth inspection of the building, both internally and externally. The surveyors assess the condition of the building structure and its various components, such as the roof, walls, floors, foundations, and surroundings. They also inspect for any potential defects or issues, such as damp, rot, or structural problems. The surveyor fills in a previously prepared questionnaire and then compiles a written report, which includes a detailed description of the property, and any issues identified.

The assessment of building deformation was conducted through visual assessment in the field using a questionnaire with qualitative descriptive categorization ranging from ‘no damage’ to ‘destroyed-collapsed’ building (Table 1). The starting point for the applied categorization and degree of damage was based on the national Guidance for a unique methodology for the natural disaster damage assessment in the Republic of Serbia (Official Gazette of SFRY N° 27 of 10 April 1987). The categorization primarily refers to buildings damaged during earthquakes, but it can be used in assessments of damage caused by various causes on a wider scale. More details about the appearance of the census list and the method of conducting the survey are provided in Đurić, 2020 and Đurić et al., 2022.

3.3. Visual interpretation of high-resolution UAV images

The aircraft DJI MATRICE 600 PRO industrial hex copter, equipped with a mounted DSLR camera (Canon EOS 6D) with a resolution of 20.2 megapixels and a focal length of 24 mm, was used to conduct aerial photogrammetric surveys. In March 2019, a UAV collected almost 2200 photographs. After manually eliminating oblique and blurry imagery, 2082 images remained for additional processing. The overlap between flight path rows was about 60% while the overlap between forward images was at least 90%. Averaging a pixel size of 2.2 cm, the UAV was flying 80 meters above the take-off station. The entire landslide area was covered by seven flights (Abolmasov et al., 2021).

Table 1. A qualitative description table was used for the building structural damage classification at the 'Umka' landslide with a color scheme applied to the Main map.

Building damage class		Structural damage description
Without damage		Buildings where no damage due to sliding has been recorded.
Slightly damaged		Buildings where minor damage was recorded in the form of minor cracks in the walls, minor damage to the roof, and small cracks in the mortar facade or chimney.
Damaged		Buildings with moderate damage to the roof covering, glass, chimneys, and facade, as well as partially cracked plaster, observable from the exterior of the building. Structural elements such as load-bearing and partition walls may also exhibit cracks or partial shearing. This level of damage may have an impact on the structure's overall integrity and stability, requiring further assessment, and possible repairs or maintenance to restore it to a safe and functional state.
Heavily damaged		Buildings that have sustained major damage and deformations of individual or all elements of its construction. These types of damages are characterized by the presence of gaping cracks, collapsed sections, significant parts of the facade or plaster that have fallen off, and significant damage to partition and load-bearing walls. Such levels of damage indicate significant harm to the structural integrity and stability of the building, and further assessment and repairs are essential to restore the building functionality and safety.
Destroyed/Collapsed		Buildings whose structural system, or significant parts of it, have undergone partial or complete destruction. This level of damage results in a loss of structural integrity and stability, rendering the building uninhabitable or even dangerous to approach.

SfM is a photogrammetric technique that uses sequences of two or more 2D photos of the same item taken from multiple camera positions (passive sensor) to determine the 3D structure of the object as well as the position and orientation of the camera. The SfM process of 3D reconstruction of the environment is quite automated and simpler than classical photogrammetry, where the external and internal parameters of images are known, due to the relatively large number of photos that can be taken with the same sensor but from different positions. Imaging occurs in the visible spectrum, and the idea behind reconstructing the environment in three dimensions is comparable to how human eyesight creates three dimensions as well.

UAV images of the 'Umka' landslide were processed and a high-density point cloud was created using the SfM. Afterward, the point cloud was used along with the aerial images for creating the high-resolution Digital Terrain Model (DTM) and Orthomosaic (Zhang et al., 2023). A stereo pair was created from an Orthomosaic and a DTM using the ILWIS *Stereo Pair from the DTM tool* (Hengl & Gruber, 2003). The Orthomosaic image was displayed over the terrain and the stereo pair was analyzed on the computer screen (split screen mode) with a screen-scope in 3D. The process of creating the Map involved analysis of the stereo pair generated in such a manner, assigning appropriate symbology to each mapped element using established engineering geological guidelines.

Orthomosaic was an essential foundation for the hazard and risk analysis of the 'Umka' landslide, as it provided the means to accurately determine the spatial positions and affected areas of elements at risk (Đorđević et al., 2022). It is noteworthy that the photogeological analysis preceded the field research, and that the field research phase was initiated based on the findings of the analysis. Without the application of this method, it would have been challenging to conduct efficient field research.

The categorization of damage was primarily based on the assessment of the actual road surface damage, which was visible from orthophotos (Figure 2). The condition of the road structure itself, which was only present on state road N°26, was verified through field inspections. Each road was divided into segments by deformation, ranging from 'no damage' to 'permanently destroyed', based on a qualitative description,

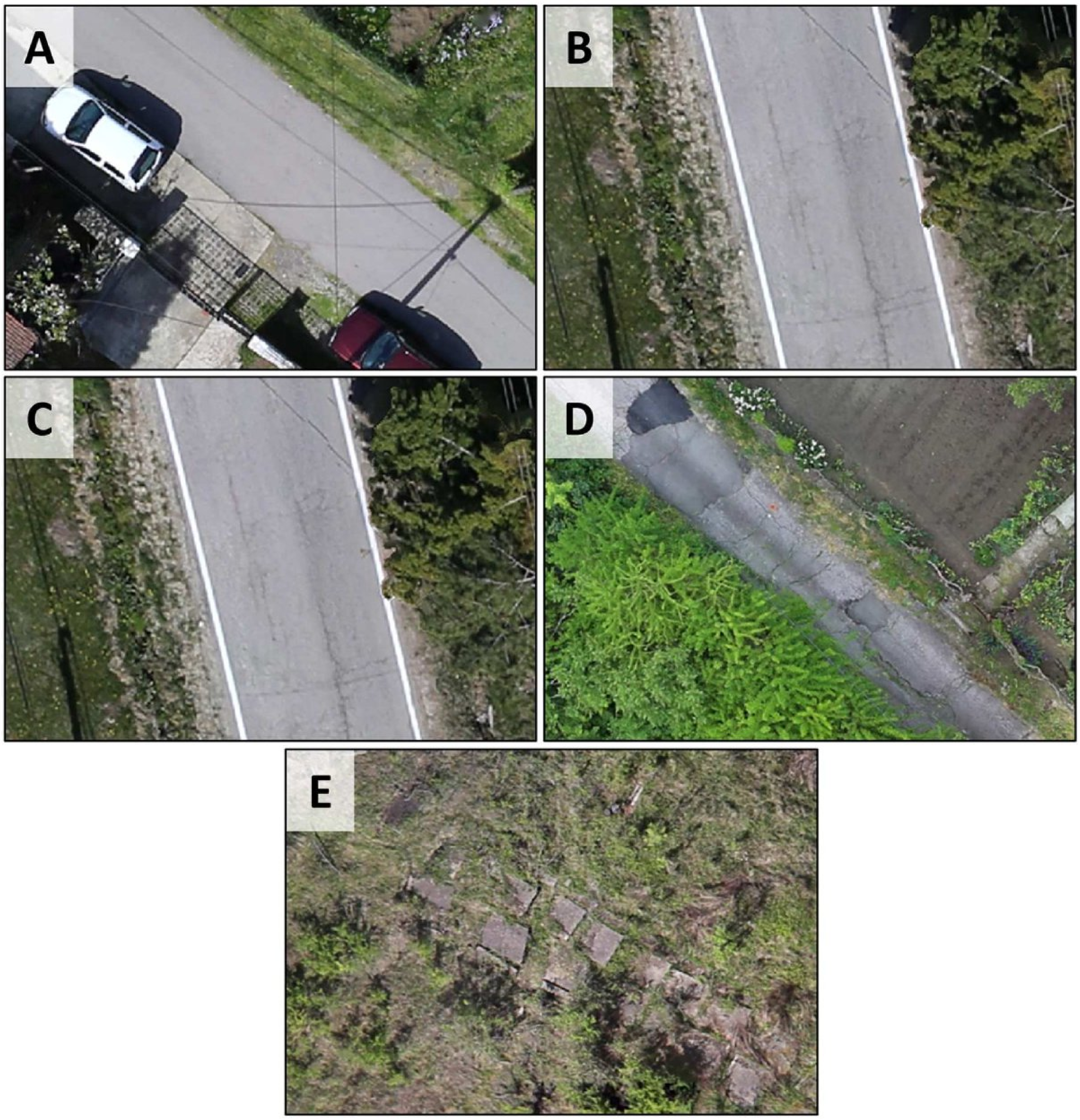

Figure 2. Details of roadway infrastructure based on the criteria outlined in Table 2: **(A)** Road without damage; **(B)** Slightly damaged road; **(C)** Damaged Road; **(D)** Heavily damaged road; **(E)** Destroyed Road.

as shown in Table 2. Additionally, each segment was assigned an attribute record indicating the type of road pavement, which was classified based on literature and identification of materials during field mapping. The classification includes concrete, asphalt, gravel, and dirt roads.

4. Results & discussion

4.1. Terrain deformation

A qualitative analysis of high-resolution images revealed several phenomena associated with the 'Umka' landslide, including main and secondary scarps determined by the presence of scars and shadows, with visible vertical displacement, large gaping cracks in the ground, large separate blocks within the sliding body, ridges, outcropping bare ground, and potential water accumulation in depressions. To collect data from the stereo pairs, line Shapefiles were created, within which separate domains were defined for classifying the observed shapes into various categories. These included the landslide boundary, classified as certain or uncertain, and active or dormant, the main scarp, the secondary major and minor scars, the ridging and bulging of the landslide, riverbanks at risk of subsidence and collapse, and the road embankment delineation and denivelation. These data were then combined with the results of detailed engineering geological mapping of the terrain.

4.2. Building damage

As part of the inventory of elements at risk within the 'Umka' landslide area, a total of 375 buildings were identified, in which 495 inhabitants reside. Each building

Table 2. Qualitative description table used for the road network damage classification at the 'Umka' landslide with a color scheme for the Main map.

Road network damage class		Damage description
Without damage		The surface, base, and subbase layers are without visible damage or with minor damage.
Slightly damaged		The surface, base, and subbase layers have less visible damage, which is usually characterized by small, narrow fissures in the roadway that do not significantly affect the traffic flow. Regular maintenance is required.
Damaged		The surface, base, and subbase layers with visible damages are usually characterized by opened cracks and deformations of the roadway or embankment, which can partly affect the flow of traffic. Remediation is required.
Heavily damaged		The surface, base, and subbase layers have pronounced severe visible damage, which is characterized by gaping cracks and deformations of the road, with missing parts of the pavement and damage to the embankment, and vertical displacement/denivelation. These damages represent a serious threat to the safety of all road users and require immediate measures of rehabilitation or reconstruction.
Destroyed/Collapsed		The surface, base, and layer courses no longer exist or are damaged to such an extent that it is not possible to carry out any form of traffic across it.

was photographed, (Figure 3) and its location was determined using the coordinates of its central point, with the prior written or oral consent of the property or building owner or resident. Over 95% of the owners and residents provided consent for the recording of their building, while a significant number of abandoned and neglected buildings were only recorded structurally. Buildings that were not accessible were observed from a distance and a rough assessment of all parameters required in the questionnaire was made. As many as 18 buildings in the landslide area are no longer physically located in their original positions. These building were mapped using remote sensing techniques (Figure 3), based on archival or newly captured aerial photographs. For these buildings, attributes were recorded to a level that was possible using only visual identification as a tool. For example, it was possible to recognize the type of roof covering, the useful square footage of the base of

Figure 3. Aerial images of two destructed buildings on the 'Umka' landslide that are inaccessible and surveyed by UAV remote sensing.

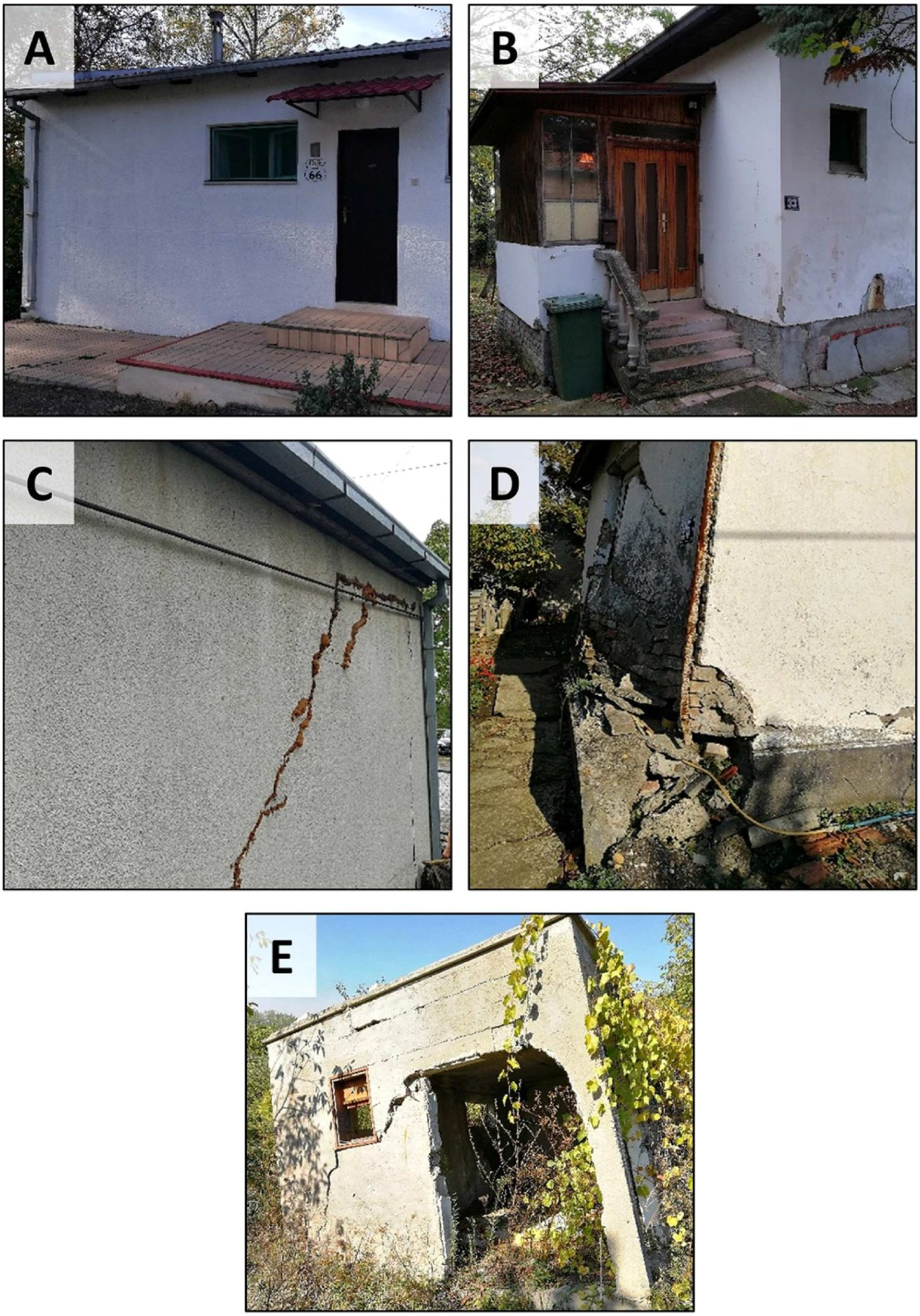

Figure 4. Photographs of selected buildings on the 'Umka' landslide by damage category based on the criteria outlined in Table 1: **(A)** Building without damage; **(B)** Slightly damaged building; **(C)** Damaged building; **(D)** Heavily damaged building; **(E)** Destroyed/ Collapsed building.

the ground floor, and the purpose of the building, given that most of these objects were in a so-called weekend settlement. However, it was not possible to precisely determine the number of floors of the building, the type of foundation, the material of the walls, their level of damage, etc (Figure 4).

A total of 375 buildings were mapped and recorded as part of this study, with 357 of these

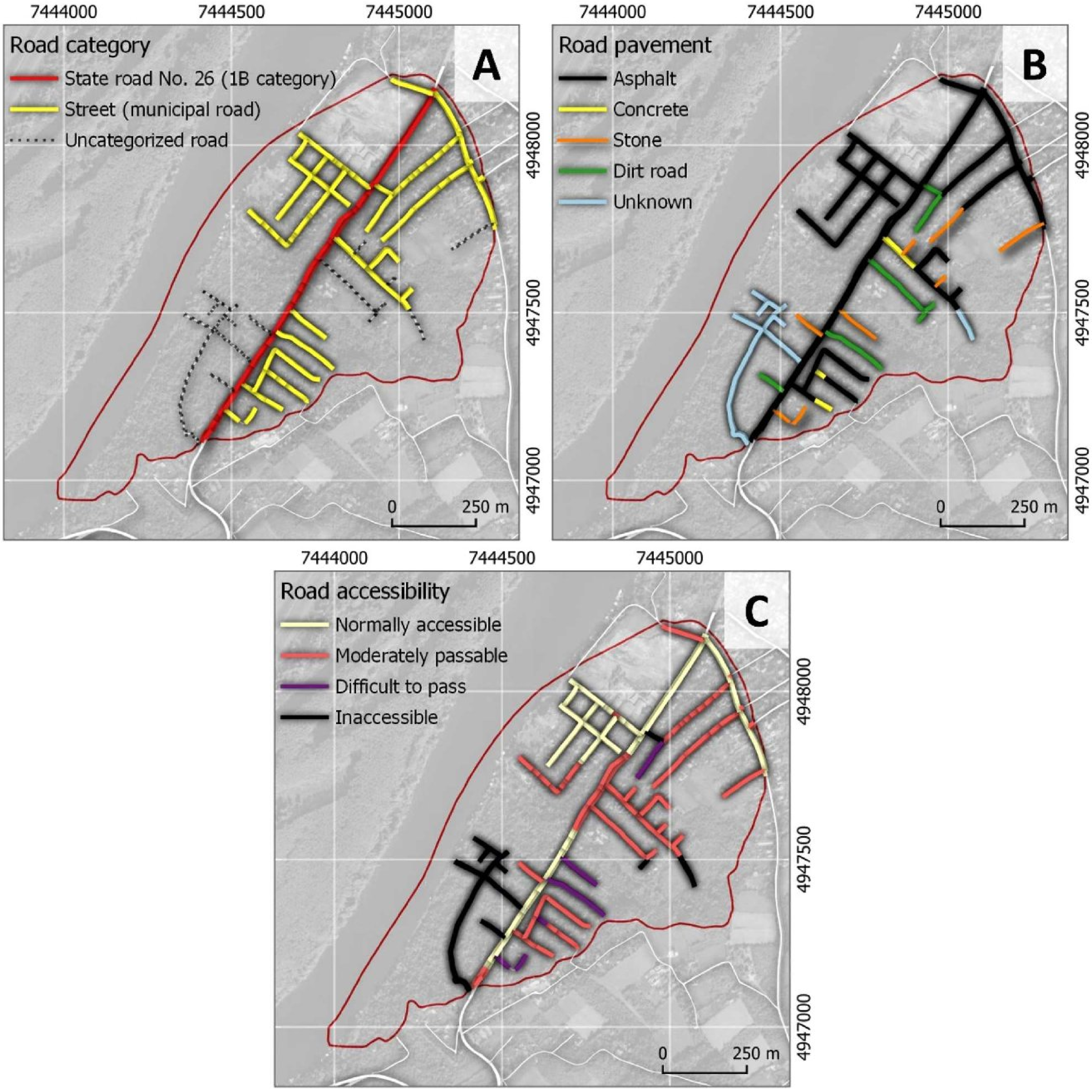

Figure 5. **(A)** Road category map of the 'Umka' landslide; **(B)** Road pavement map of the 'Umka' landslide; **(C)** Road accessibility map of the 'Umka' landslide.

buildings surveyed and mapped through direct observation in the field. The remaining 18 buildings were mapped using remote sensing techniques. A household census was conducted for 226 of the listed buildings, while it was not possible to conduct a census for the remaining 149 buildings, which were either abandoned, demolished, or uninhabited. For these buildings, only a typological classification was performed based on the census list. The collected data were entered into a GIS database that was created for this study, with all structural data being entered. This allowed for statistical analysis and the creation of maps based on individual typological parameters. While not all the data collected was necessary for the analysis of landslide risk, it was collected for future research and analysis. This study only presents those parameters that are relevant and significant for the assessment of landslide risk and for evaluating the current situation.

Results of the building survey showed that only 69 (18%) buildings were without any deformation and 90 (24%) buildings had slight damage from the landslide. 100 (27%) buildings were classified as damaged and 74 (20%) as heavily damaged while 42 buildings were identified as damaged or destroyed.

4.3. Road infrastructure damages

The landslide 'Umka' crosses a total of 7.1 km of roads of various categories, as shown in Figure 5A. The most prevalent type of road within the landslide area is streets (municipal roads), which account for 4.15 km

(58%) of the total road length. Unclassified roads, which account for 1.75 km (25%) of the total road length, are the next most common. Lastly, State Road N°26, with a total length of 1.2 km (17%), also spans across the landslide area.

Within the landslide area, 1.35 km (19%) of roads are undamaged, 1.35 km (19%) are slightly damaged, 1.4 km (20%) are moderately damaged, and 1.68 km (24%) are significantly damaged. Additionally, 1.32 km (18%) of the roads were permanently destroyed. The distribution of road damage is illustrated in the Main map followed by a pie chart diagram.

Based on the material of the pavement within the 'Umka' landslide, the road surface is mostly comprised of asphalt (Figure 5B) with a total length of 4.4 km (61%). Dirt roads account for 0.8 km (11%), followed by stone pavement, which has a total length of 0.7 km (9.9%). Concrete is the least represented, accounting for 0.2 km (3.1%). It was not possible to determine the type of material for the 1 km (15%) of roads that have been destroyed (classified as Unknown).

In terms of accessibility, 2.2 km (31%) of the roads are considered normally accessible, 3 km (44%) are moderately passable, 0.6 km (8%) are difficult to pass, and 1.2 km (17%) are inaccessible. The map of traffic roads is illustrated in (Figure 5C).

The analysis further showed that only 38% of the roads are undamaged or have minor damage, while 62% are damaged, significantly or completely, preventing their regular use. The biggest risk is the deformation of the state road N°26, which significantly slows down the traffic and affects its safety, thus preventing safe access and regular use of the street infrastructure for most of the residents.

5. Conclusion

The detailed map of the 'Umka' landslide emerges as a valuable resource, striking a balance between complexity and accessibility for both professionals and the public. Through intuitive design features, such as clear symbology and color-coded representations, with clearly delineated boundaries of elements at risk, the map ensures that a diverse audience can extract meaningful insights and provides a solid foundation for further landslide risk assessment.

Our study underscores the critical importance of engineering geological mapping, demonstrating its versatility for various applications. By examining geological and geotechnical investigations spanning several decades (1978–2019), a complete understanding of the 'Umka' landslide dynamic nature has been achieved. The integration of methodologies, including engineering geological mapping, building surveying, and visual interpretation of high-resolution UAV images, enriches the analysis, providing a refined perspective.

The complex geological composition of the 'Umka' landslide, characterized by varying depths, water permeability challenges, and pronounced spatiotemporal anisotropy, unravels the complexities inherent in this dynamic phenomenon. Terrain deformation analysis and detailed damage assessments of building structures and road infrastructure reveal the far-reaching impact of the landslide, necessitating a holistic risk evaluation.

A standout feature of our research lies in the emphasis on user-friendly landslide map. The inclusion of clear symbology and design elements not only caters to professionals in the field but also serves as a powerful tool for public awareness and preparedness. This map goes beyond conventional representations, offering a complete visualization that aids in decision-making at various levels.

In conclusion, this research not only deepens understanding of the 'Umka' landslide but also sets a benchmark for future studies. The integration of diverse methodologies and data sources provides an extensive analysis of the geotechnical conditions, paving the way for informed decision-making by authorities and stakeholders involved in the landslide risk management and urban planning of the affected region. The insights gained extend beyond 'Umka', holding relevance for landslide-prone regions globally, marking a significant stride in the ongoing efforts towards effective disaster risk reduction and community resilience.

Software

Free GIS software, ILWIS 3.31 (University of Twente in the Netherlands) was utilized for the creation and photogeological analysis of Unmanned Aerial Vehicle (UAV) photogrammetry images. Open-source QGIS 3.28 (QGIS Development Team) was used for the manipulation of the spatial data and cartographic presentation as well. Open-source vector graphics editor Inkscape ('The Inkscape Project') was used for preparing the main map layout and for pie charts. GNU Image Manipulation Program GIMP, (GIMP Development Team), a free and open-source raster graphics editor was used for image manipulation and image editing. WebODM ('WebODM Authors') a free, user-friendly, extendable application was used for drone image processing and for generating georeferenced maps, point clouds, and textured 3D models from UAV images.

Note

1. According to official Average Annual Daily Traffic Load Report for 2022 year (State Road IB category N° 26 – section 02622) issued by Public Enterprise Roads of Serbia (https://www.putevi-srbije.rs).

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No potential conflict of interest was reported by the author(s).

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Data availability statement

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request. However, for safety reasons, the shapefiles of the buildings are not available.

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