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QUANTITATIVE IDENTIFICATION OF LANDSLIDE SCARPS USING UAV LIDAR TERRAIN PROFILES: CASE STUDIES FROM JAKOPOVEC AND LAZ BISTRIČKI (CROATIA)

Abstract:

The UAV LiDAR terrain model provides accurate identification of various landslide-related features, with a specific emphasis on terrain discontinuities known as scarps. This research aims to develop a quantitative method for identifying scarps using terrain-profile analysis of UAV LiDAR DTM. The research considers two landslide-prone areas located in northern Croatia: Jakopovec and Laz Bistrički. The results show smooth slope geometry with one scarp area for Jakopovec and multiple slope break areas for Laz Bistrički. The terrain profile provides reliable differentiation between landslide-related scarps and drainage features. The research shows that terrain profile analysis is a simple and reliable method for identifying landslide-related scarps using UAV LiDAR technology.

Keywords: UAV LiDAR, landslides, digital terrain model, terrain profiles, scarp detection

КВАНТИТАТИВНА ИДЕНТИФИКАЦИЈА КЛИЗИШНИХ ОЖИЉАКА ПРИМЈЕНОМ UAV LIDAR ТЕРЕНСКИХ ПРОФИЛА: ПРИМЈЕРИ ЈАКОПОВЕЦ И ЛАЗ БИСТРИЧКИ (ХРВАТСКА)

Сажетак:

UAV LiDAR модели терена омогућују детаљно препознавање геоморфолошких обиљежја повезаних с клизиштима, посебно дисконтинуитета рељефа познатих као клизишни ожиљци. У овом раду приказан је квантитативни приступ идентификацији ожиљака примјеном теренских профила добивених из UAV LiDAR дигиталних модела терена. Анализирана су два клизиштима подложна подручја у сјеверној Хрватској, Јакоповец и Лаз Бистрички. Резултати показују релативно уједначену геометрију падине с једном зоном ожиљка на локалитету Јакоповец те више зона прекида нагиба и сложенију морфологију на локалитету Лаз Бистрички. Теренски профили омогућили су поуздано разликовање клизишних ожиљака од дренажних облика рељефа. Истраживање показује да анализа теренских профила представља једноставну и поуздану методу идентификације клизишних ожиљака из UAV LiDAR података.

Кључне ријечи:UAV LiDAR, клизишта, дигитални модел терена, профили, идентификација клизишних ожиљака

1. INTRODUCTION

Landslides are a common natural hazard in hilly regions, often threatening infrastructure, settlements, and transportation routes. Landslide morphology identification is of primary importance for slope stability analysis. Terrain discontinuity, also known as a landslide scarp, is one of the primary geomorphological parameters associated with landslide occurrence. It defines the boundary between stable and unstable terrain. Precise identification of such parameters requires high-resolution digital terrain models capable of capturing minute terrain variations.

Recent advancements in the application of airborne LiDAR technology have significantly improved the detection and identification of landslides compared with traditional topographic methods. LiDAR-based digital terrain models can accurately describe terrain, especially in dense vegetation, which is a primary requirement for geomorphological analysis. Recent studies have proved the applicability of LiDAR data for the accurate identification of landslides, including the identification of main scarps, secondary scarps, blocks, and accumulation zones, as discussed in various publications by [1], [2], [3].

The recent developments in the application of LiDAR technology using UAVs are capable of acquiring high-resolution terrain data, which is more flexible compared to the conventional method. UAV-based LiDAR data are capable of acquiring high-density point cloud data, which is more useful for accurate engineering-scale analysis. Recent studies have proved the applicability of UAV-based LiDAR data for the accurate identification of landslides compared to regional LiDAR data, as discussed in various publications by [4], [5], [6].

Nevertheless, landslide scarps are often identified through the visual analysis of terrain derivatives such as hillshade or slope maps. Although such methods are successful at identifying landslide scarps, they are sometimes associated with misinterpretations of terrain features, such as drainage channels or anthropogenic features. Thus, the need for quantitative methods in the identification of landslide scarps has been emphasized in contemporary geomorphology [7], [8]

Terrain profiles are derived from high-resolution DTMs. The analysis of terrain profiles is a simple yet effective method for quantifying slope features. Such methods are helpful for direct measurement of elevation or slope changes. Moreover, terrain profile analysis is helpful in the objective validation of geomorphological interpretations. Nevertheless, the application of terrain profiles in the identification of landslide scarps is limited in the context of earlier studies [9].

This study aims to develop a quantitative approach to identifying landslide scarps by analyzing terrain profiles derived from UAV LiDAR DTM models. The study area is identified in two landslide-prone regions in northern Croatia: Jakopovec and Laz Bistrički.

2. STUDY AREAS

The methodology used in this research was applied in two landslide-prone areas in northern Croatia: the Jakopovec area near Varaždin and Laz Bistrički in the Hrvatsko Zagorje region. The areas are characterized by are prone to landslides. The selected areas are representative of landslides in northwestern Croatia, where slow slope deformation and rotational landslides are common.

2.1. JAKOPOVEC

The research area in Jakopovec is located in a region south of Varaždin, in a gently undulating hilly landscape, with elevations ranging from 190 m to 230 m above sea level. The topography of this area is characterized by smooth slopes with moderate inclinations and is mostly used for agriculture.

The geomorphological analysis of this area, based on UAV LiDAR terrain models, indicates a simple slope morphology. The upper part of the slope has stable terrain conditions with small elevation variations, while in the central part of the slope, a smooth transition is observed without abrupt terrain discontinuities. The lower part of this slope is characterized by a reduced slope gradient and small microrelief features of colluvial deposits.

The Jakopovec area is an example of a slope with weakly expressed geomorphological indicators of landslide phenomena. The profile of this area shows smooth elevation variations and wide slope-transition zones, with no clear indication of a scarp.

2.2. LAZ BISTRIČKI

The Laz Bistrički study area is located in the Hrvatsko Zagorje region. The Hrvatsko Zagorje region is characterized by steeper slopes and more pronounced relief than the Jakopovec study area. The height of the slopes in the Laz Bistrički study area ranges from about 340 m to 390 m above sea

level. The terrain in the Laz Bistrički study area comprises irregular hillslopes with small drainage channels and active or dormant landslides.
The UAV LiDAR terrain model reveals complex geomorphological features in the Laz Bistrički study area. These features comprise multiple slope discontinuity areas, irregular terrain morphology, as well as the presence of microrelief. The central section of the slope in the Laz Bistrički study area indicates terrain breaks characterized by geomorphological scarps. The lower section of the slope in the Laz Bistrički study area indicates the presence of hummocky terrain and convex terrain associated with landslide accumulation areas.
Compared to the Jakopovec study area, the Laz Bistrički study area indicates more complex landslide morphology and a more pronounced geomorphological expression of landslide phenomena. The terrain profile indicates the presence of multiple slope breaks with height differences exceeding 15-20 m.

3. DATA AND METHODS

3.1. UAV LIDAR DATA ACQUISITION

High-resolution terrain data for both study areas was obtained using an unmanned aerial vehicle (UAV), the DJI Matrice 350 RTK, equipped with a LiDAR sensor (Zenmuse L2) and a GNSS/INS positioning system. UAV LiDAR data collection was performed in favorable weather conditions to ensure reliable point cloud collection and positioning. The average point density of the LiDAR data was approximately 293 (Jakopovec)–150 (Laz Bistrički) points/m². Flight altitude was approximately 80 m (Jakopovec) and 120 m (Laz Bistrički) above ground level, with a flight speed of 9.44 m/s (both sites). High-density three-dimensional points were useful for detailed terrain modeling and geomorphological analysis. The density of the points was sufficient to obtain information about terrain changes that cannot be easily obtained from other topographic data sources. Ground point classification was performed using standard filtering algorithms implemented in DJI Terra. The classified points were used to generate digital terrain models representing bare-earth terrain. The obtained digital terrain models had sufficient resolution (0.5m) to provide detailed information on slope morphology and discontinuities in the terrain resulting from landslide activity.

3.2. DIGITAL TERRAIN MODEL PROCESSING

Digital terrain models (DTMs), obtained using UAV LiDAR, are the primary data used to analyze terrain geomorphology. The generation of terrain-derivative data within a Geographic Information System (GIS) environment has been useful for identifying geomorphological features associated with landslide phenomena. Hillshade models have been developed using DTMs and employing various illumination directions to improve the visualization of terrain morphology. The use of various illumination directions has been found beneficial for the clear demarcation of slope breaks and smaller-scale terrain discontinuities. Slope models have been developed by utilizing DTMs for the quantitative interpretation of terrain geometry. The use of slope maps has been found beneficial for identifying areas with steeper terrain and distinguishing landslide scarps from the surrounding terrain.The use of DTMs, hillshade models, and slope maps has been found beneficial for geomorphological terrain interpretation and selecting profile locations.

3.3. TERRAIN PROFILE EXTRACTION

Terrain profiles were created using UAV LiDAR-derived DTM data to enable quantitative assessment of slope geometry. The profiles were created to ensure they crossed the slopes nearly perpendicular to the principal terrain discontinuities, as depicted in the hillshade images. Three terrain profiles were selected for each study area. The selection of the profiles was based on the aim of ensuring that different geomorphological features were represented. These features include the areas of stable terrain, areas of transition from one slope to another, and areas with significant terrain discontinuities. Terrain profiles enable the direct measurement of various parameters of the terrain, including the following:

- - differences in elevation
- - differences in slope
- - width of the areas of slope breaks
- - total relief

Terrain profiles were created using GIS techniques and exported as elevation-distance graphs.

3.4. IDENTIFICATION OF LANDSLIDE SCARPS

In order to reduce the subjective effects in the identification of scars, quantitative parameters based on the geometry of the terrain profile were used. A zone of scarp is characterized by the following conditions:

(1) Local elevation discontinuity ($\Delta H \geq 10$ m)

(2) A significant increase in the local slope gradient compared with the surrounding terrain

(3) The presence of a slope break separating the upper stable terrain from the lower displaced material

These conditions were used in the study for all terrain profiles.

Landslide scarps were identified through the integration of visual interpretation and quantitative analysis of terrain profiles. The initial identification of potential areas for the presence of landslide scarps was performed using hillshade models and slope models. Candidate areas for the presence of landslide scarps were identified as terrain areas exhibiting significant slope discontinuities or localized changes in slope gradient. The terrain profiles were used to validate the candidate areas for the existence of landslide scarps. Three representative profiles were selected for each study area in order to capture the main geomorphological variability of the slope, including upper slope, central slope, and lower slope conditions. The terrain profiles were used to distinguish between landslide scarps and other features in the terrain, such as drainage channels or anthropogenically altered terrain areas.

The landslide scarps were identified as the terrain areas that exhibited localized elevation discontinuities or significant slope breaks that differentiated the terrain from the altered slope material.

The integrated approach ensured the successful identification of geomorphological scarps, with reduced uncertainty compared to the visual interpretation approach.

4. RESULTS

Geomorphological analysis of UAV LiDAR-derived DTM and terrain profiles enabled the identification and characterization of slope morphology in the two study areas. The results show clear differences between the Jakopovec and Laz Bistrički areas in terms of terrain complexity and the occurrence of scarp landforms. Terrain profiles enabled the acquisition of data on elevation differences, slope changes, and terrain discontinuities. An integrated analysis of the DTM, hillshade model, and terrain profile analysis enabled reliable differentiation between landslide scarps and non-landslide terrain features. Profile relief values were calculated as the difference between the maximum and minimum elevations along each terrain profile. Scarp height was determined as the elevation difference across the main slope-break zones identified in the terrain profiles.

4.1. JAKOPOVEC

The terrain's morphological characteristics are relatively smooth, and the geomorphological indicators of slope instability are limited. The results of the Hillshade analysis indicate that the slope geometry is relatively uniform, and only minor terrain discontinuities are present (Figure 1).

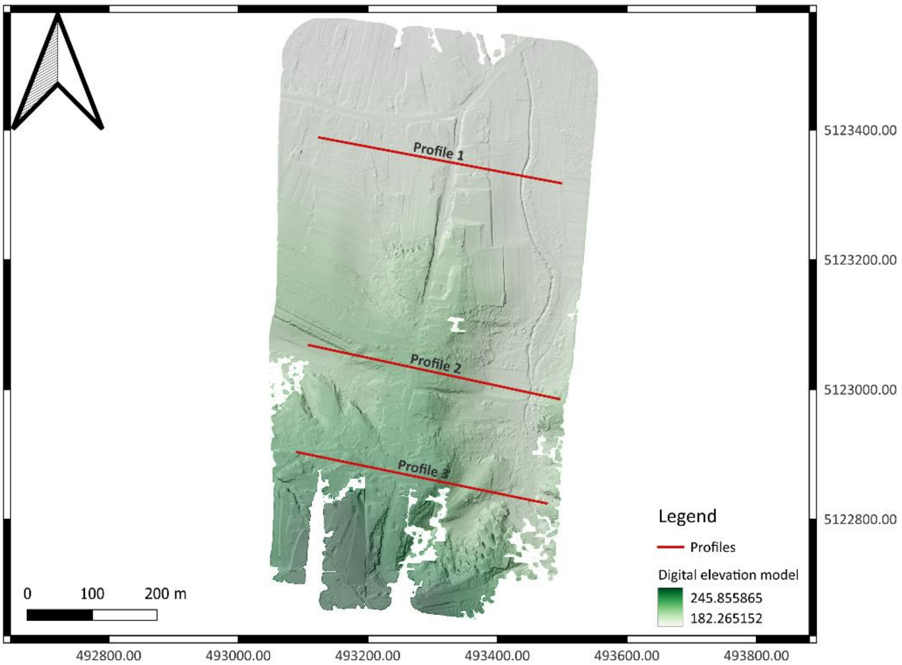

Figure 1. UAV LiDAR-derived DTM of the study area in Jakopovec, indicating the position of the terrain profiles (created by author).

Three terrain profiles were defined across the slope to characterize different slope positions. Quantitative results are presented in Table 1.

4.1.1. Profile 1 – Upper Slope

Profile 1 (Figure 2) shows stable terrain conditions with minimal elevation variations. The profile shows smooth terrain geometry, with no sudden slope variations or elevation discontinuities. The total relief of this profile is about 2-3m, indicating a nearly horizontal terrain. No scarps are present along this profile.

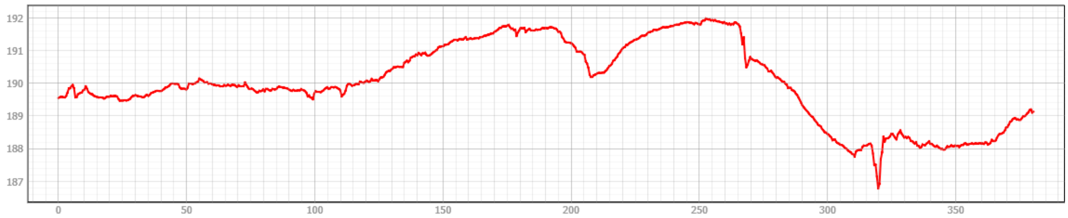

Figure 2. Profile 1 – Upper Slope (Jakopovec) (created by author).

4.1.2. Profile 2 – Central Slope

Profile 2 (Figure 3) is defined over the central part of the slope and shows smooth elevation variations. A slope transition zone is present in the central part of this profile. No sudden terrain discontinuities are present. Elevation variations are about 25m along this profile, indicating hillslope relief and no presence of a scarp.

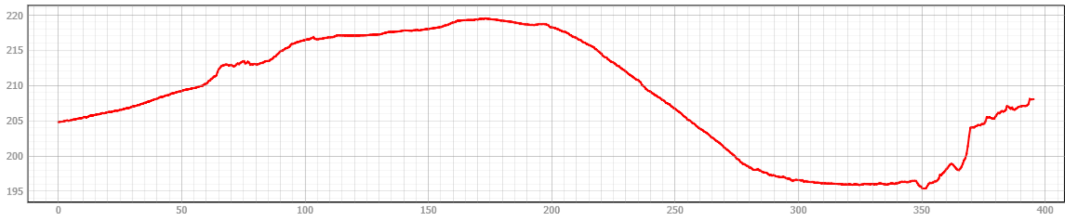

Figure 3. Profile 2 – Central Slope (Jakopovec) (created by author).

4.1.3. Profile 3 – Lower Slope

Profile 3 (Figure 4) is defined over the steepest part of the slope and shows the greatest elevation variations. A slope break zone is present in the central part of this profile. The slope break zone is characterized by an elevation variation of 15-18m over a horizontal distance of 40-50m, indicating a broad geomorphological scarp zone. The lower part of this profile shows reduced slope gradients, indicating the presence of colluvial deposits.

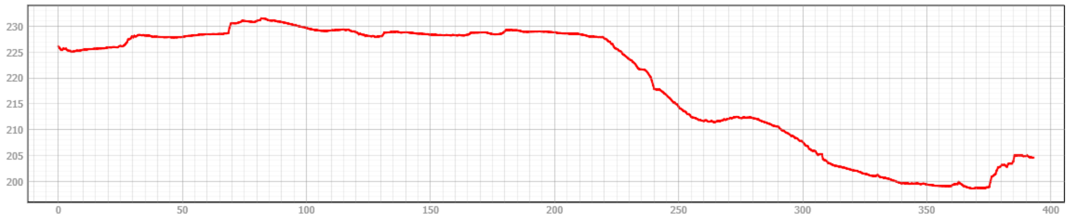

Figure 4. Profile 3 – Lower Slope (Jakopovec)

Table 1. Terrain profile parameters for the Jakopovec study area

Profile	Length (m)	Elevation range (m)	Relief (m)	Scarp height (m)	Scarp width (m)	Interpretation
Profile 1	≈400	189-192	≈3	-	-	Stable terrain
Profile 2	≈400	195-220	≈25	-	-	Smooth slope
Profile 3	≈400	199-231	≈32	15-18	40-50	Broad scarp zone

The Jakopovec site shows predominantly smooth slope morphology with only one clearly defined scarp zone. The terrain geometry indicates a relatively weak geomorphological expression of slope instability. The identified scarp zone is characterized by gradual elevation changes rather than abrupt terrain discontinuities.

4.2. LAZ BISTRIČKI

Terrain morphology is more complex in the Laz Bistrički site than in the Jakopovec site. Several terrain discontinuity features with irregular micro-relief have been identified as a result of landslide activity (Figure 5).

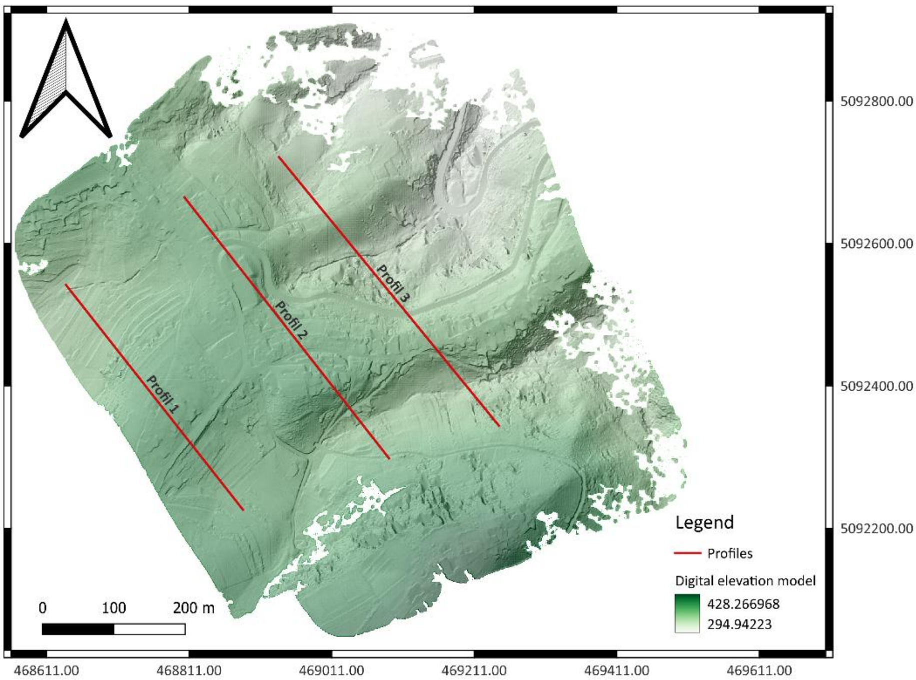

Figure 5. UAV LiDAR-derived DTM for the Laz Bistrički site with indications of terrain profile locations (created by author).

Terrain profiles have been selected for the upper, central, and lower slope areas. Quantitative results are presented in Table 2.

4.2.1. Profile 1 – Upper Slope

Terrain profile 1 (Figure 6) shows smooth terrain geometry, typical of background hillslope morphology. The elevation differences along this profile amount to approximately 35 m; however, the slope is smooth with no clear indication of scarps. There are some minor terrain irregularities; however, they can be considered minor variations in the terrain.

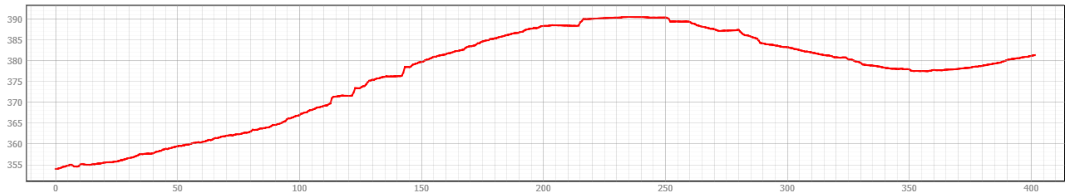

Figure 6. Profile 1 – Upper Slope (Laz Bistrički) (created by author).

4.2.2. Profile 2 – Central Slope

Terrain profile 2 (Figure 7) has been selected for the central part of the slope. Several terrain features can be noted along this profile. A small depression is noted in the upper part of the profile with an elevation difference of approximately 4-5 m. The maximum elevation difference is approximately 22-23 m; however, this feature is V-shaped, indicating a drainage incision feature.

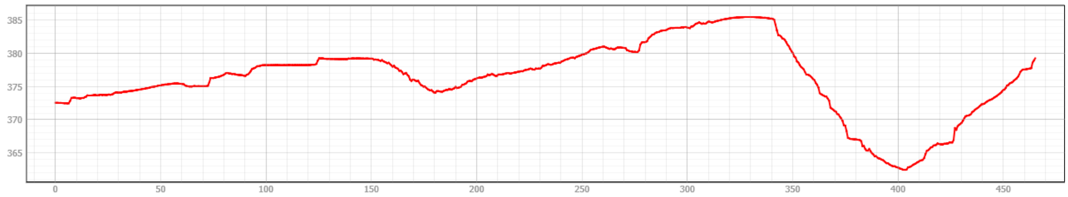

Figure 7. Profile 2 – Central Slope (Laz Bistrički) (created by author).

4.2.3. Profile 3 – Lower Slope

Terrain profile 3 (Figure 8) shows the most pronounced geomorphological features. Two slope break features have been noted along this profile. One slope break feature shows an elevation difference of approximately 18 m over a horizontal distance of approximately 60-70 m. The second slope break feature shows an elevation difference of approximately 20 m over a horizontal distance of approximately 70-90 m. Between the two slope break features, there is some irregular terrain morphology due to landslide activity.

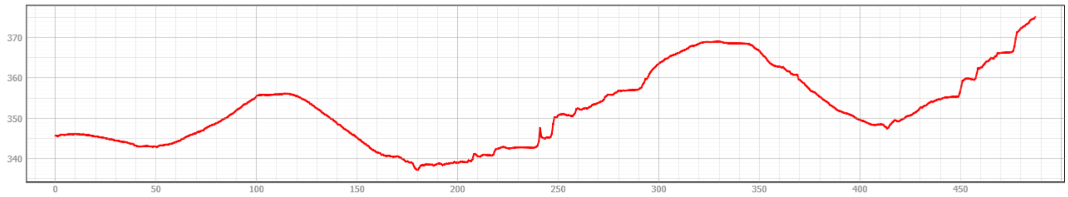

Figure 8. Profile 3 – Lower Slope (Laz Bistrički) (created by author).

Table 2. Terrain profile parameters for the Laz Bistrički study area

Profile	Length (m)	Elevation range (m)	Relief (m)	Scarp height (m)	Scarp width (m)	Interpretation
Profile 1	≈400	354-390	≈36	-	-	Stable slope
Profile 2	≈470	362-385	≈12	-	-	Drainage incision
Profile 3	≈500	338-375	≈37	18-20	60-90	Multiple scarp zones

4.3. COMPARISON OF STUDY AREAS

Comparison of terrain profiles shows clear differences in geomorphological complexity between the two sites (Table 3).

Table 3. Comparison of geomorphological characteristics

Parameter	Jakopovec	Laz Bistrički
Relief	Low-moderate	Moderate-high
Number of scrap zones	1	2
Maximum scarp height	15-18m	18-20m
Terrain complexity	Low	High
Landslide expression	Weak	Strong

Jakopovec is characterized by smooth terrain with a single extensive scarp zone, whereas Laz Bistrički has multiple slope-break zones with a complex landslide morphology. Analysis of the terrain profile has proven to be successful in differentiating landslide scarps from drainage features and smooth slope transitions.

5. DISCUSSION

The results suggest that digital terrain models obtained from UAV LiDAR systems are useful for reliable identification of geomorphological features associated with landslide activity. The results of this research have confirmed that terrain profile-based analysis is a simple and efficient approach for identifying slope discontinuities and validating geomorphological analyses derived from LiDAR-derived terrain models. Although only three profiles per site were analyzed, they were selected to represent key geomorphological zones, which was sufficient for identifying major slope discontinuities.

5.1. RELIABILITY OF SCARP IDENTIFICATION

The identification of landslide scarps is often based on geomorphological analysis of terrain-model derivatives, such as hillshade or slope maps. The results of this research have shown that although a hillshade visualization approach is efficient for identifying terrain discontinuities in both study areas, it may yield ambiguous results when identifying landslide scarps. The results have shown that several geomorphological features identified as potential landslide scarps were actually drainage incisions or slope transitions, rather than geomorphological discontinuities.

The results of this research have shown that this limitation is more apparent in identifying landslide scarps in the Laz Bistrički study area. The results have shown that a geomorphological feature identified in a hillshade visualization is actually a drainage channel, not a landslide scarp. The results of this research have also shown that the terrain profile exhibits a V-shape characteristic of a drainage channel or an erosional process. This has enabled a clear distinction between a landslide scarp and a slope break. This has highlighted the importance of quantitatively validating geomorphological analysis obtained from a LiDAR-derived terrain model.

A terrain profile approach is an objective method for validating geomorphological analysis derived from a LiDAR-derived terrain model. The results of this research have shown that a profile approach is effective for differentiating among smooth slopes, drainage incisions, and landslide scarps.

5.2. DIFFERENCES BETWEEN STUDY AREAS

The two study areas show considerable differences in the geomorphological expression of slope instabilities. The Jakopovec area has relatively smooth terrain with a weak expression of terrain discontinuity. The terrain profiles show that the terrain changes gradually, with only one zone exhibiting considerable expression as a scarp.

The Laz Bistrički area has relatively more complex terrain morphology, with multiple slope-break zones. The terrain profiles show several elevation discontinuities and irregular terrain shapes typical of rotational landslides. The presence of multiple scarp zones indicates that slope instabilities are more complex or have multiple phases than in the Jakopovec area.

This shows that the terrain profile analysis is applicable across different terrain types, with varying geomorphological expressions of slope instabilities. The methodology is therefore applicable to both areas with subtle terrain discontinuity features and areas with well-expressed landslide features.

5.3. ADVANTAGES OF TERRAIN-PROFILE-BASED ANALYSIS

The results show that terrain profile-based analysis offers several advantages for identifying landslide scars compared with other methodologies. The first advantage is that the methodology is straightforward to implement, as it only requires a high-resolution digital terrain model and any GIS software. The terrain profiles provide direct geometric information regarding the terrain morphology.

Compared to other automated geomorphometric methods that require data processing before analysis, the terrain profile-based analysis is simple to execute because it does not require any preprocessing.

In addition, the method enables the objective verification of the identified features on the hillshade and slope maps. Hence, the reliability of landslide scarp identification can be enhanced.

5.4. LIMITATIONS

Despite the benefits of the UAV LiDAR-based terrain model, the method has limitations. First, identifying the scarp zones requires interpreting terrain morphology and selecting representative profile locations. There are various profile locations, which may lead to different interpretations of slope morphology, especially in complex terrain.

The profiles are one-dimensional representations of the terrain morphology. Hence, it is not feasible to interpret the three-dimensional landslide morphology using the profiles. In this regard, the identification of scarp morphology needs to be coupled with the analysis of terrain-model derivatives, such as hillshade and slope.

Moreover, it is not feasible to interpret the geomorphology of the landslides from the terrain models, especially with respect to subsurface conditions. Hence, the geomorphology-based analysis needs to be coupled with the field investigations.

The results revealed that the terrain profile-based method is reliable and effective for identifying landslide scarps using a UAV LiDAR-based terrain model.

6. CONCLUSION

This study uses quantitative methods to identify geomorphological scarps by analyzing terrain profiles derived from UAV LiDAR. The use of such high-resolution terrain data enables detailed analysis of slope morphology and reliable determination of elevation discontinuities associated with landslide phenomena. The results from applying the proposed methodology in the two study areas confirm the effectiveness of terrain profile analysis in differentiating among the three types of slope features. The study area at Jakopovec is characterized by relatively smooth terrain with weakly expressed geomorphological discontinuities, whereas the study area at Laz Bistrički is characterized by more complex slope morphology, with several landslide scarps and strong expression of terrain variability. The proposed methodology is especially important for differentiating real landslide scarps from terrain features that strongly resemble landslide phenomena in the hillshade visualizations. The results from the proposed study confirm the effectiveness and reliability of the methodology for quantitative identification of landslide scarps using terrain profile analysis and UAV LiDAR-derived DTMs. The proposed methodology is based solely on the use of high-resolution DTMs and can support engineering investigations and preliminary landslide assessments. The proposed methodology improves the reliability of geomorphological interpretation results using UAV LiDAR-derived DTMs and can support landslide mapping, slope stability, and terrain analysis in landslide-prone areas.

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